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Dolomitized Pahasapa Limestone (Mississippian), northeastern sector of the Black Hills, South Dakota, petrography and geological setting

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DOLOMITIZED PAHASAPA LIMESTONE

(MISSISSIPPIAN), NORTHEASTERN SECTOR

OF THE BLACK HILLS, SOUTH DAKOTA,

PETROGRAPHY AND GEOLOGICAL SETTING

BY

ABDULLATIF NAJJAR, 1945-

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ABSTRACT

The carbonates of the Mississippian Pahasapa Limestone in the northeastern sector of the Black Hills outcrops were examined in order to ascertain specific characters of the lithology in this area where the formation is predominantly a dolomite in contrast to adjacent areas where it is mainly a limestone.

The Pahasapa seems to be uniform in thickness at the study areas and maintains a thickness of about 550 feet. Because of poor exposures, usually at the base or top, complete sections could not be measured.

Much of the Pahasapa consists of coarsely crystalline dolomite containing varying proportions of crinoid plates, gastropods, bryozoans, corals, and ostracodes, all dolomitized to varying degrees.

Eight rock types are recognized in the Pahasapa carbonates in the study areas. These rock types are:

1. Dolosparite
2. Biodolosparite
3. Crinoidal biodolosparite
4. Biodolomicrite
5. Dolomicrite
6. Sparite
7. Intrasparite
8. Dolointramicrite

These rock names were constructed from a modified Folk terminology and are based on semi-quantitative analysis of about 200 thin sections of rock samples. Bar diagrams were drawn alongside the

stratigraphic sections which proved to be useful in comparing rock types between different outcrops. However, there was sufficient variability in the constituents from section to section so that correlations based on the bar diagrams were not feasible.

The original Pahasapa sediment is inferred to have consisted of inorganic calcitic ooze with considerable to dominant amounts of calcitic organic debris resulting from the disintegration and abrasion of hard parts of organisms that lived in shallow and relatively clear water. Abundant bedding planes and cross-bedding attest to relatively high energy conditions.

The process by which and the time at which these sediments became dolomitized is not well understood, as is the case with other dolomitized limestones. The uniformity and the widespread distribution of the dolomite in the area of study is used to support the contention that the change to dolomite took place early in the history of the sediment, i.e., it was essentially penecontemporaneous with the sediment.

ACKNOWLEDGEMENTS

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Thanks are due to my friend Abd El-Aziz Borahay, who helped me in preparing the photomicrographs.

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INTRODUCTION

This thesis describes and interprets the petrography, stratigraphic relations, the dolomitization pattern in the sections, and origin of the Mississippian Pahasapa carbonates of the northeastern Black Hills, South Dakota.

The Pahasapa carbonates in this area are of exceptional interest because it represents an area where dolomite has developed in contrast to surrounding areas where limestones are dominant.

The Pahasapa forms a series of prominent, scenic cliffs in the canyons which radiate from the Black Hills.

The thickness of the Pahasapa Limestone, which is the formal name of this unit, ranges from less than 100 feet as Darton reported (1925, p. 6) to more than 550 feet in the Black Hills where the study was made. The thickness remains uniform and maintains a thickness close to 550 feet. Because of poor exposures, usually at the base or top, complete sections could not be measured.

Constituents in the carbonates were determined by hand specimen and thin-section study. Amounts of constituents were estimated using a visual estimation chart as a guide. The microscopic investigation and the determination of the carbonate constituents was very essential in introducing a classification of the Pahasapa carbonates.

LOCATION OF SECTIONS

Seven sections from the most prominent outcrops of the Pahasapa formation in the northeastern Black Hills, South Dakota were studied and collected in the field. The outcrops are located between latitudes 44^{o} 15' to 44^{o} 30', and from longitudes 103^{o} 25' to 104^{o} 00' (Fig. 1).

The following is the location of each measured section:

1. Iron Creek Section. Section along Iron Creek, a tributary to Spearfish Canyon, 10½ miles from the mouth of the Canyon of Spearfish Creek. SW¼, Sec. 19, NW¼, Sec. 30, T. 5 N., R. 2 E., and SW¼, Sec. 24, T. 5 N., R. 1 E., Maurice and Savoy Quadrangles (Fig. 2).
2. Little Spearfish Canyon Section. Along west bluff of Little Spearfish Creek, 0.3 mile southwest of Timon Campground. NW¼, Sec. 10, T. 4 N., R. 1 E., Savoy Quad. (Fig. 3).
3. Crow Peak Section. Northwest flank of Crow Peak. SE¼, Sec. 15, T. 6 N., R. 1 E., Maurice Quad. (Fig. 4).
4. Bear Butte Creek Section. Section measured in bluff in East Wall in Bear Butte Canyon. 2.4 miles upstream from junction with Boulder Creek. NE¼, NE¼, Sec. 35, T. 5 N., R. 4 E. Lawrance Co. Deadman Mountain Quad. (Fig. 5).
5. Boulder Creek Section. 1.3 miles from U.S. Highway 14 along unpaved road which parallels Boulder Creek, bluff and cliff at west side of Boulder Creek. SW¼, NW¼,

Sec. 23, T. 5 N., R. 4 E., Sturgis Quad. (Fig. 6).

6. Deadwood Section. Along U.S. Highway 85 and 14A, 1½ miles NE Deadwood, South Dakota. E½, SE¼, Sec. 14, and NW¼, SW¼, Sec. 13, T. 5 N., R. 3 E., Deadwood North Quad. (Fig. 7).

7. Little Elk Creek Section. Section along north side of Little Elk Creek Canyon between the Red Gate and the White Gate. 2.4 miles up Little Elk Creek Canyon road from junction with I-90. N½, NE¼, Sec. 7, T. 3 N., R. 6 E., Piedmont Quad. (Fig. 8).

Fig. 1. Index map. Numbers show the general locations of the stratigraphic sections. More exact locations are given on pages 2 and 3. Grid shown on map represents townships. Taken from U. S. G. S., Rapid City 1:250,000 scale regional map.

R. 1 E.
R. 5 E.
LOOKOUT PEAK
Spearfish
3929
3817
ELKHORN PEAK
4000
Whitewood
Sturgis
Galena
Elmore
Cheyenne Crossing
5498
Roubaix
Elk Creek
CUSTER PEAK
North Boxelder Cr.
Middle Boxelder
LAWRENCE COUNTY
PENNINGTON COUNTY
PILOT KNOB
CASTLE PEAK
FLAG MOUNTAIN
6031
Deerfield
1
2
3
4
5
6
7
->3Mi

Fig. 1

Fig. 2. Location of Iron Creek section. The section measured along the traverse indicated by the two X's and red line. Taken from U. S. G. S. 7½' Savoy Quadrangle.

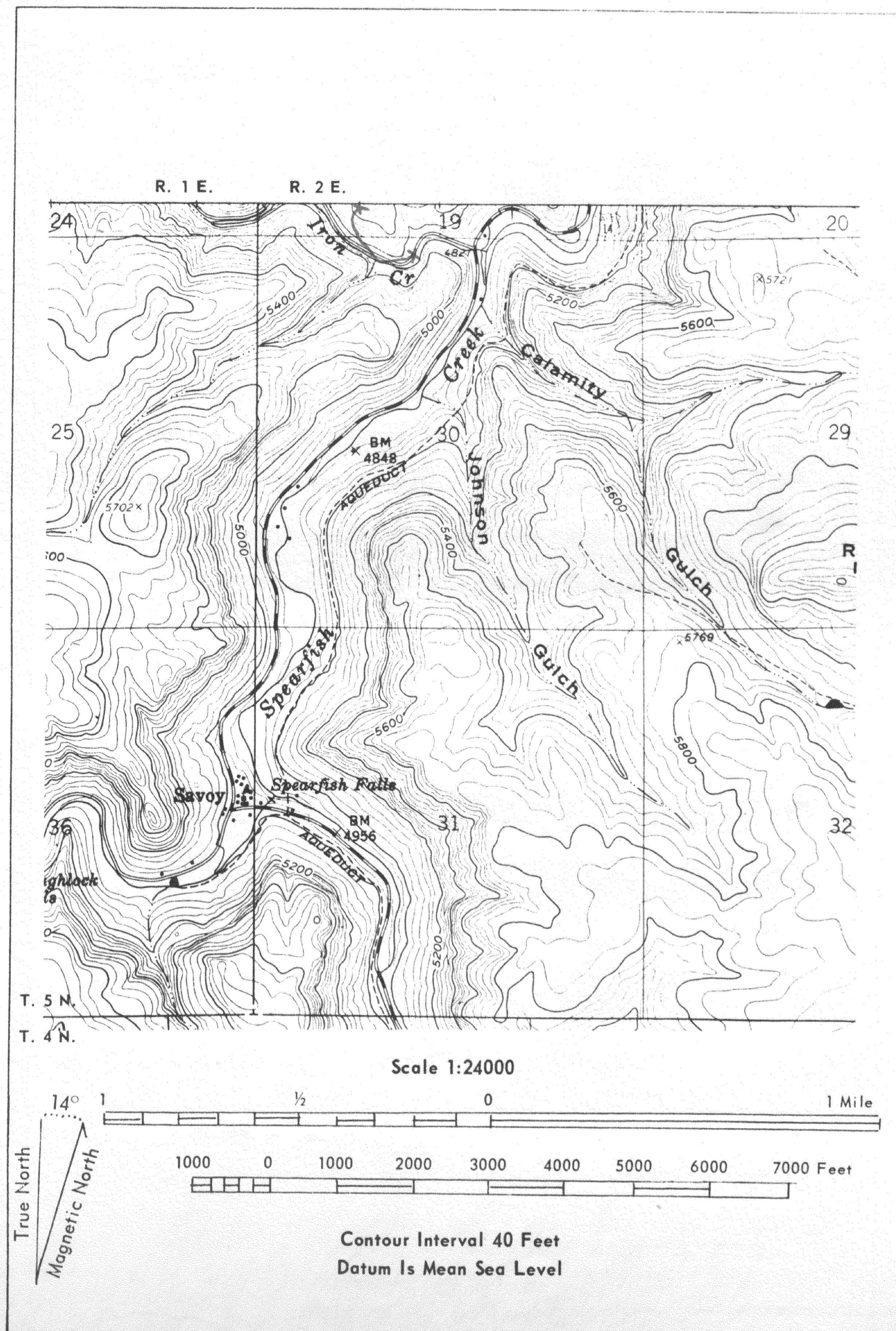

R. 1 E.
R. 2 E.
24
19
20
Iron Cr
Creek
Calamity
25
30
29
BM 4848
AQUEDUCT
Johnson
Gulch
5702
5721
5769
5000
5200
5400
5600
5800
Spearfish
Gulch
Savoy
Spearfish Falls
BM 4956
36
31
32
T. 5 N.
T. 4 N.
Scale 1:24000
1
½
0
1 Mile
1000
0
1000
2000
3000
4000
5000
6000
7000 Feet
14°
True North
Magnetic North
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 2

Fig. 3. Location of Little Spearfish Canyon section, Spearfish, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Savoy Quadrangle.

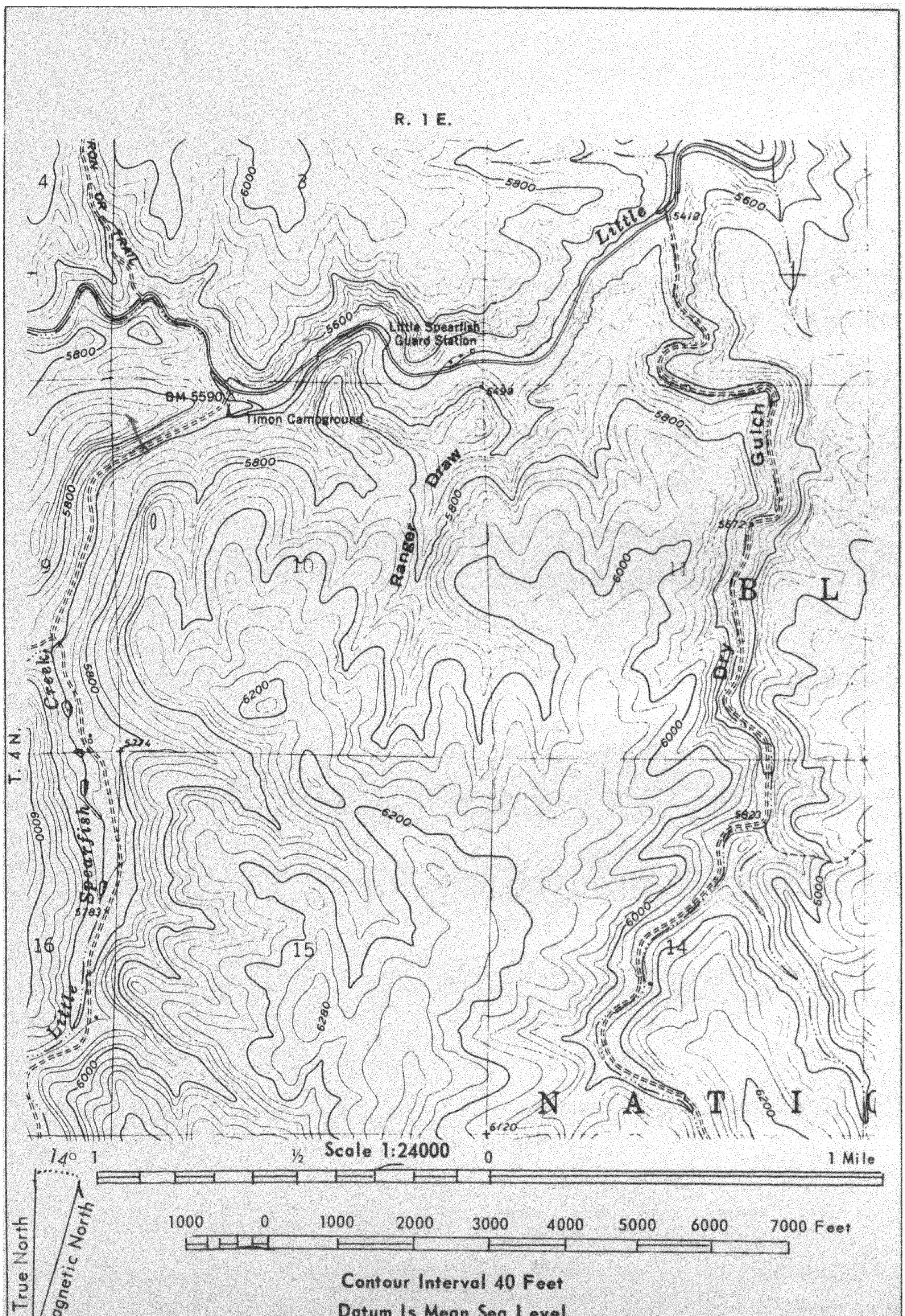

R. 1 E.
T. 4 N.
IRON OR TRAIL
Little Spearfish Guard Station
BM 5590
Timon Campground
Little
Ranger Draw
Dry Gulch
Little Spearfish Creek
B L
N A T I
5800
5600
6000
6200
6280
6120
5412
5499
5672
5774
5783
5823
4
3
9
10
11
14
15
16
Scale 1:24000
1 ½ 0 1 Mile
1000 0 1000 2000 3000 4000 5000 6000 7000 Feet
14°
True North
Magnetic North
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 3

Fig. 4. Location of Crow Peak section, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Maurice Quadrangle.

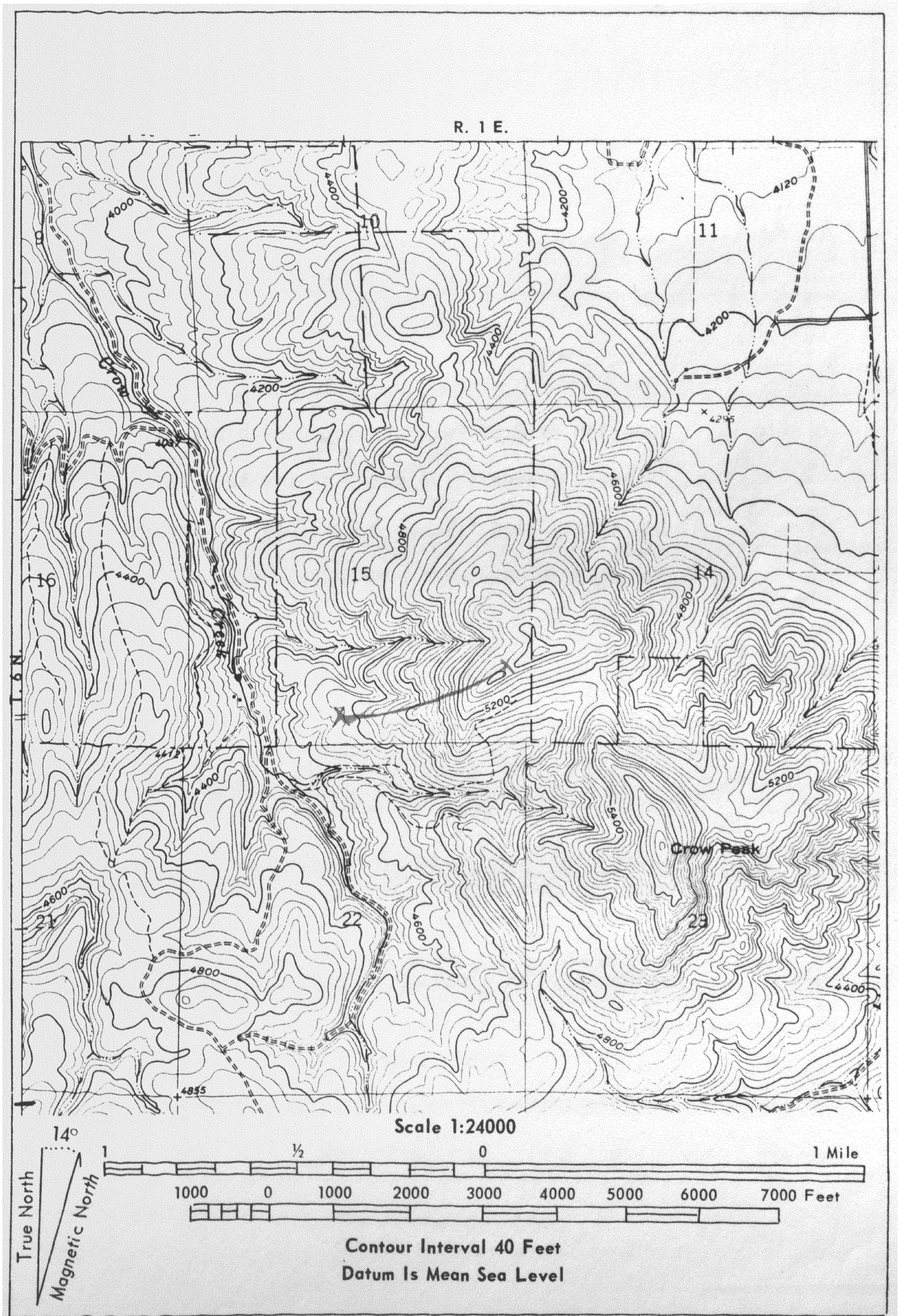

R. 1 E.
T. 6 N.
9
10
11
15
14
16
21
22
23
4000
4400
4200
4120
4600
4800
5200
5400
4037
4471
4295
4855
Crow Creek
Crow Peak
Scale 1:24000
14°
True North
Magnetic North
1
½
0
1 Mile
1000
0
1000
2000
3000
4000
5000
6000
7000 Feet
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 4

Fig. 5. Location of Bear Butte Creek section, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Deadman Mountain Quadrangle.

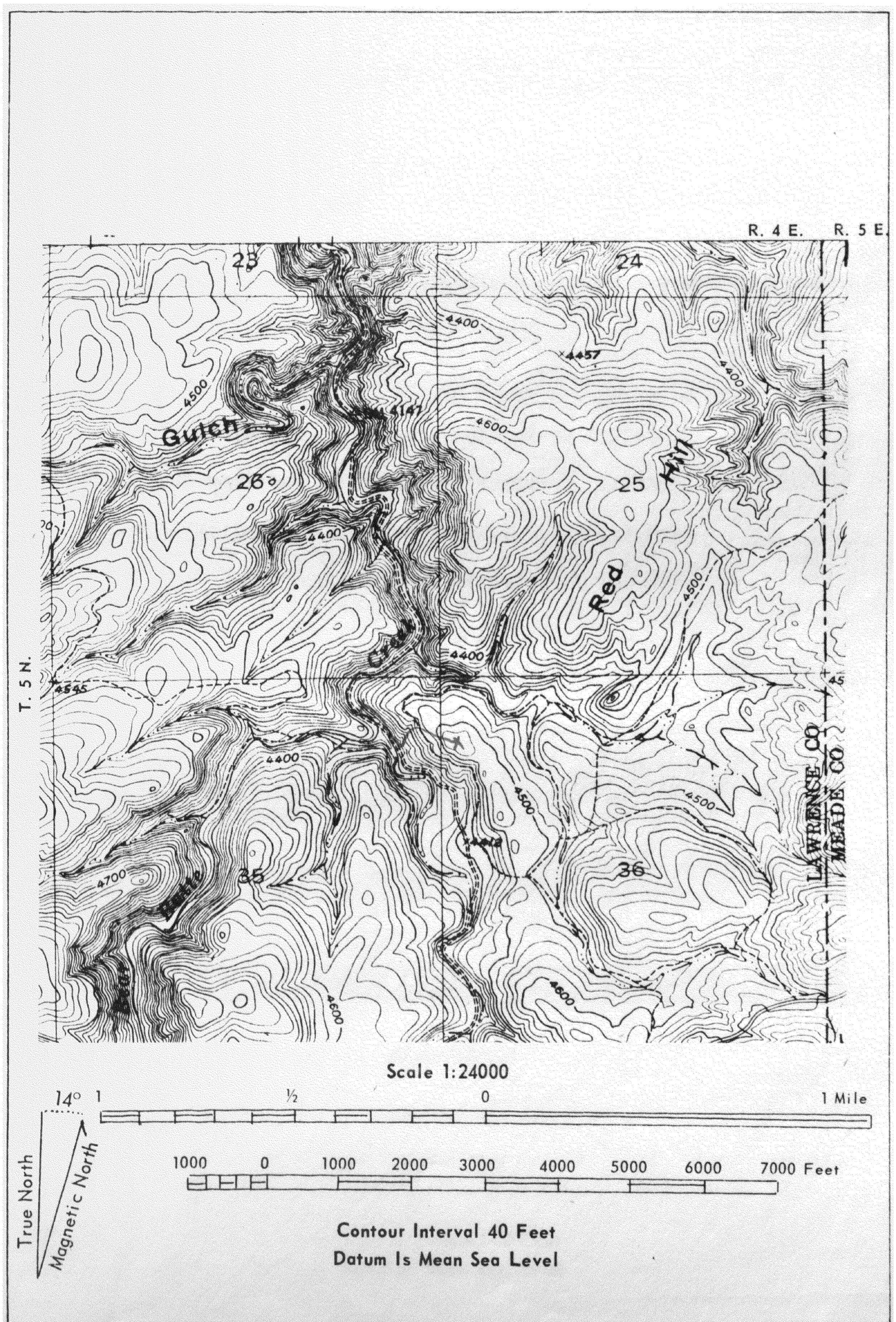

R. 4 E.
R. 5 E.
T. 5 N.
23
24
25
26
35
36
Gulch
Creek
Red
Hill
LAWRENCE CO
MEADE CO
4400
4457
4500
4545
4600
4700
Scale 1:24000
1
½
0
1 Mile
1000
0
1000
2000
3000
4000
5000
6000
7000 Feet
14°
True North
Magnetic North
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 5

Fig. 6. Location of Boulder Creek section, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Sturgis Quadrangle.

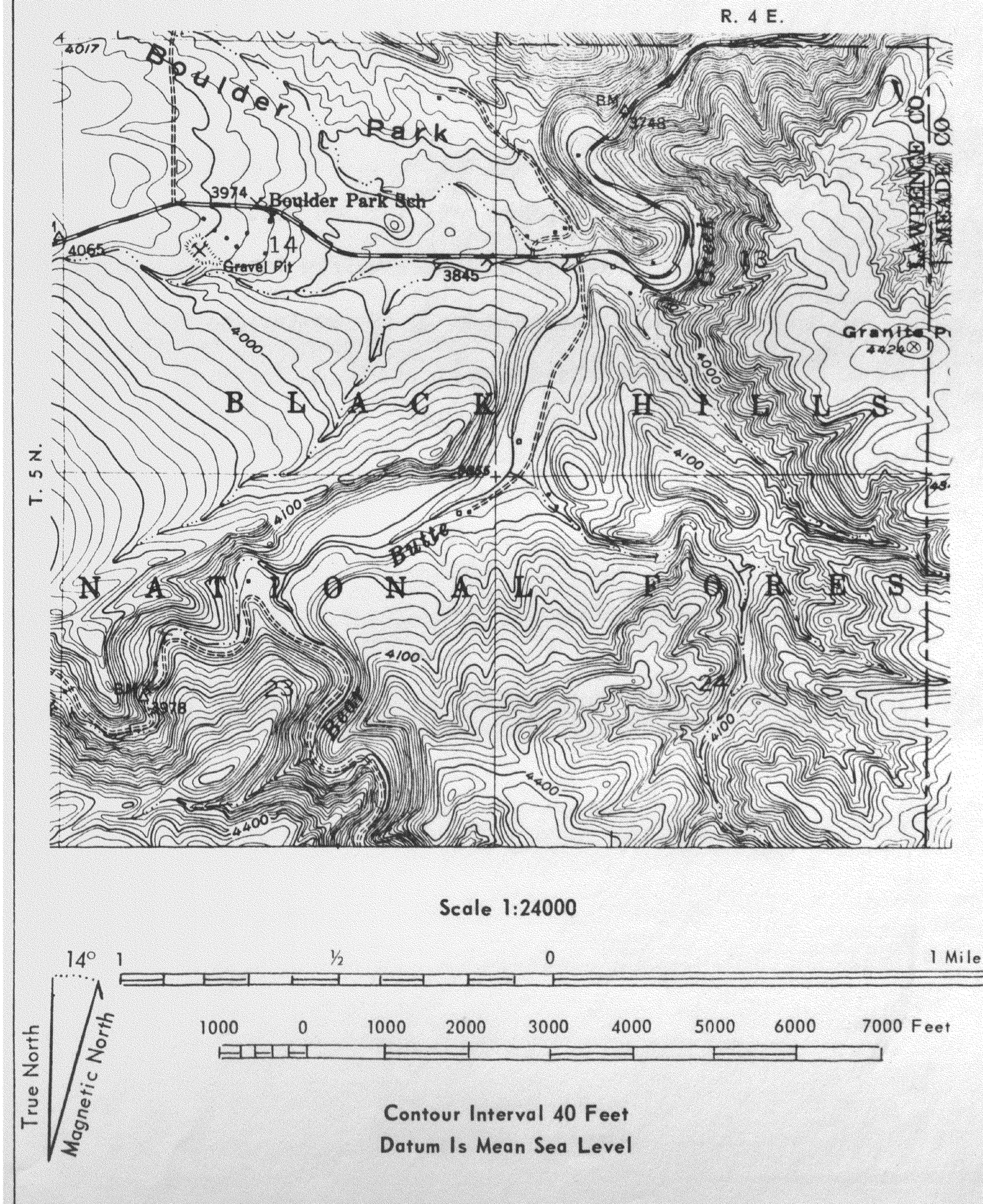

R. 4 E.
T. 5 N.
Boulder
Park
3974
Boulder Park Sch
4065
Gravel Pit
14
3845
BM
3748
Creek
13
LAWRENCE CO
MEADE CO
4000
B L A C K H I L L S
4100
Butte
N A T I O N A L F O R E S
4100
BM
3978
23
Bear
24
4400
Scale 1:24000
1 ½ 0 1 Mile
1000 0 1000 2000 3000 4000 5000 6000 7000 Feet
14°
True North
Magnetic North
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 6

Fig. 7. Location of Deadwood section, Deadwood, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Deadwood Quadrangle.

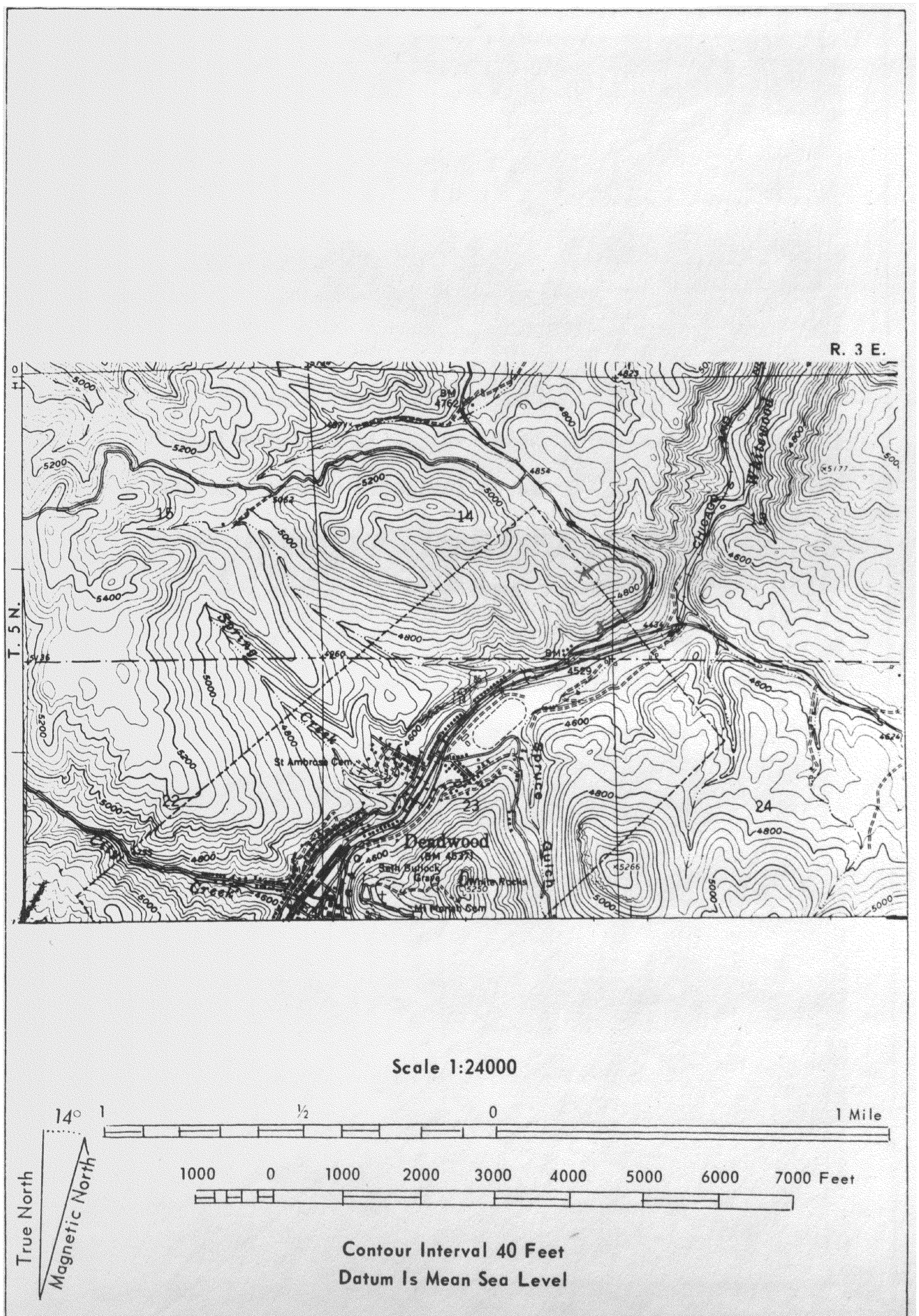

R. 3 E.
T. 5 N.
15
14
22
23
24
Spring
Creek
City
Creek
Spruce
Gulch
Whitewood
St Ambrose Cem.
Deadwood
White Rocks
Scale 1:24000
1
½
0
1 Mile
1000
0
1000
2000
3000
4000
5000
6000
7000 Feet
14°
True North
Magnetic North
Contour Interval 40 Feet
Datum Is Mean Sea Level

Fig. 7

Fig. 8. Location of Little Elk Creek section, South Dakota. Traverse indicated by red line and two X's. Taken from U. S. Geological Survey, 7½' Piedmont Quadrangle.

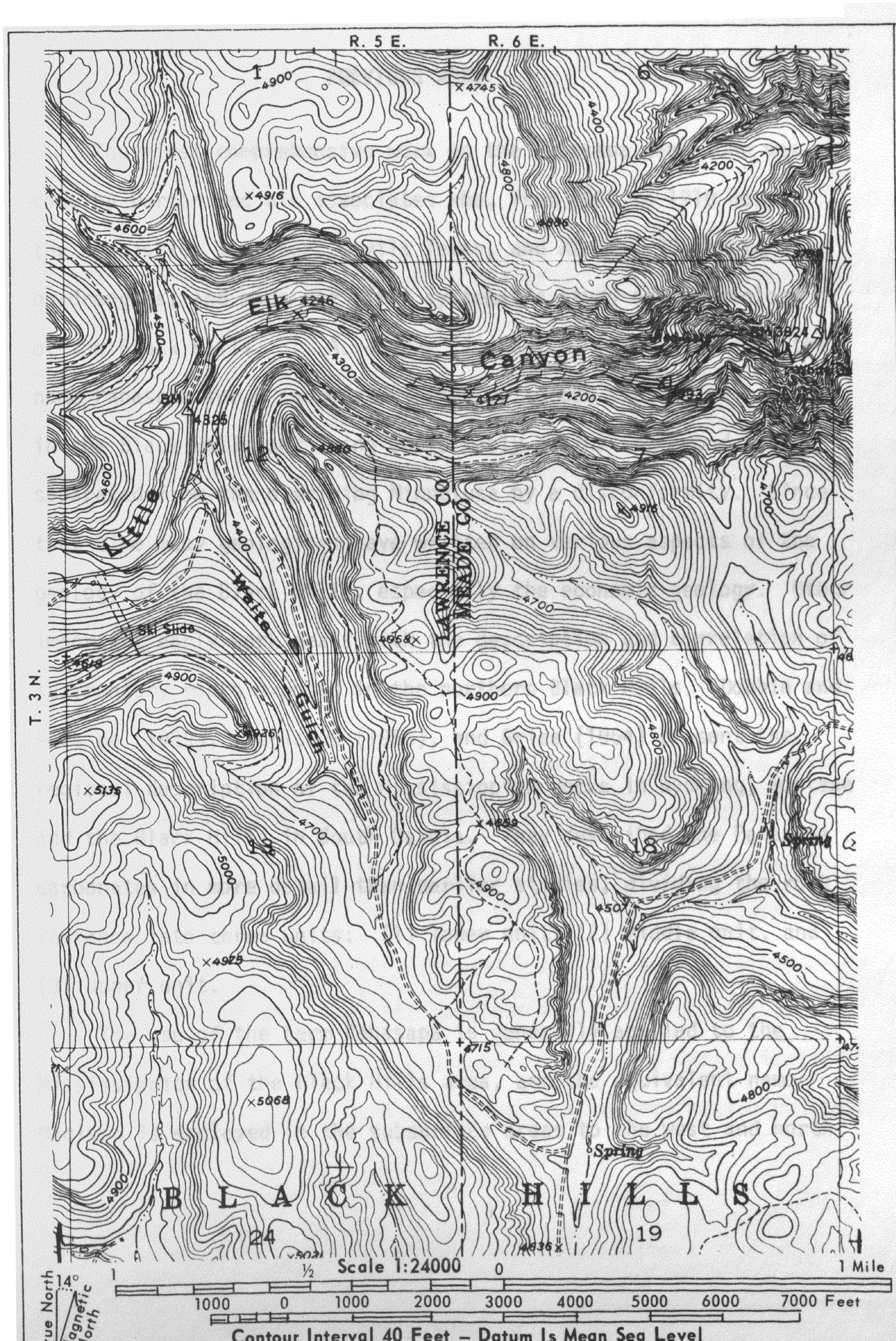

R. 5 E.
R. 6 E.
T. 3 N.
Elk
Canyon
Little
Waite
Gulch
LAWRENCE CO
MEADE CO
Ski Slide
Spring
Spring
BLACK HILLS
Scale 1:24000
1 Mile
1000 0 1000 2000 3000 4000 5000 6000 7000 Feet
True North
Magnetic North
14°
Contour Interval 40 Feet – Datum Is Mean Sea Level

Fig. 8

PREVIOUS WORK

The first comprehensive work on the Pahasapa Limestone was done by Darton and his associates who, from 1900 to 1910 mapped the Newcastle, Sundance, Devils Tower, and Aladdin 30-minute quadrangles, and made the first systematic study of the geology of the Black Hills. T. A. Jaggar (in Darton, 1901) suggested the name Pahasapa for a carbonate series up to 630 feet thick exposed in the Black Hills and lying conformably on the Englewood and separated from the overlying Minnelusa by a disconformity. Since that time many geologists have written on various aspects of the geology of the Black Hills, especially the economic geology. Other important early work deals with the description and correlation of sedimentary rocks exposed in the northern Black Hills. Dobbin and Reeside (1929), Andrichuk (1955), and Gries (1964) present the regional description of the Mississippian rocks in Wyoming, Montana and the Black Hills in South Dakota. They described the Pahasapa carbonates in more detail than earlier studies, dividing the rock sequence into three units: (1) lower unit, (2) middle unit, and (3) upper unit.

The use of the term Pahasapa is generally applied to the Mississippian of the Black Hills area, and the equivalent name Madison is employed in the subsurface areas to the west and north.

FIELD AND LABORATORY WORK

A - Field Work

The field work was done by the writer during the summers of 1969 and 1970. Seven sections were measured in the field from the most prominent outcrops in the northern Black Hills, South Dakota. Approximately 380 oriented samples were collected at one to three feet intervals and at each lithological change. Where necessary, apparent thickness was measured along traverses, after which the true thickness was computed by using the tables of Mandelbaum and Sanford (1952).

B - Laboratory Work

In the laboratory the rock samples were slabbed, polished, and stained. From the polished slabs stained acetate peels were prepared and examined under petrographic microscopes. For staining, the procedure outlined by Friedman (1959) was followed and in the preparation of stained acetate peels that of Katz and Friedman (1965). Two hundred thin sections, both stained and unstained, were prepared and studied. The thin sections were cut perpendicular to bedding planes. All the hand specimens were etched for estimation of the insoluble residue content and stained to distinguish calcite from dolomite.

STRATIGRAPHY

A - Introduction

A stratigraphic section consisting of about 11,000 feet of consolidated rocks ranging in age from Precambrian to Quaternary, and of marine, nonmarine and volcanic origin are exposed on the northern and eastern flanks of the Black Hills in the area under consideration. These rocks may be divided into 23 formations, exclusive of the surficial deposits of Tertiary and Quaternary ages. Only the Mississippian Pahasapa Formation was considered in this study.

All the sedimentary rocks, from the Cambrian Deadwood Formation to the Ft. Union Formation of Paleocene age, are nearly concordant in dip, although deposition was not continuous as shown by unconformities at the base of Minnelusa Formation (Pennsylvanian), the Gypsum Spring Formation (Middle Jurassic), the Sundance Formation (Upper Jurassic), and the Fall River Formation (Lower Cretaceous). The Ft. Union Formation and older rocks were deformed and eroded during early Tertiary time and the White River Formation of Oligocene age was deposited unconformably on the uplifted older beds. Rocks of marine and nonmarine origin are represented about equally. The Mississippian Pahasapa Formation is marine. Pennsylvanian, Permian, and Triassic rocks probably were deposited mostly in shallow marine bodies of water. Marine sediments were deposited over the area during parts of middle and late Jurassic time, followed by nonmarine deposits in late Jurassic and part of early Cretaceous time. Much of the Cretaceous is represented by a thick marine sequence beginning with the Skull Creek Shale and ending with the Fox Hills Sandstone. Younger Cretaceous and Tertiary rocks are nonmarine.

B - Regional Stratigraphy

The Mississippian system is more widespread in distribution than any of the underlying Paleozoic systems in Wyoming, South Dakota and Montana. Mississippian strata transgressed progressively over older Paleozoic strata southeastward toward the Cambridge Arch (Eardley, 1959, p. 665). Devonian rocks conformably underlie the Mississippian of western Wyoming, and in all but the southeastern part of Montana. Blackstone and McCrow (1954, pp. 38-43) reported post-Beartooth Butte Devonian strata in the Pryor-Big Horn Mountain area and indicated that Devonian rocks are more widespread in this area than had been believed heretofore.

The Ordovician Whitewood or Big Horn dolomites and limestones underlie the Mississippian in all but the southern part of the Black Hills uplift, and a part of southeastern and eastern Wyoming, east of the limit of Devonian occurrence. The Mississippian transgresses the Precambrian basement to the limit of occurrence of the Madison in northwestern Nebraska and adjoining southeastern Wyoming. In southeastern Wyoming, the Mississippian is characterized by a basal clastic (siltstone, sandstone, or conglomerate) unit which represents material reworked by the transgressing Mississippian sea (Andrichuk, 1955, pp. 2170-2210).

Agatston (1954, p. 514) described the effect of pre-Pennsylvanian erosion on the Mississippian surface in the northern and eastern Wyoming where surface channel fills (5 to 35 feet thick) commonly contain large angular fragments of limestone and chert in a quartz sand matrix.

Andrichuk (1955, p. 2178) reported that Amsden, Minnelusa, or Hartville beds overlie the Mississippian carbonate sequence in the remaining areas of Wyoming, southern Montana, and adjoining South Dakota. The lower part of the Amsden in Montana is considered Mississippian in age, but southward in Wyoming, the Amsden as well as the Tensleep, Minnelusa, and Hartville are Pennsylvanian.

C - Devonian and Mississippian Rocks At The Study Areas

1. Devonian - Mississippian Rocks: In many areas of the Rockies and the Mid-continent there is a formation which is considered to be partly Devonian and partly Mississippian in age. This is currently considered to be the case of the Englewood Formation.

Englewood Formation - the name Englewood was suggested by T. A. Jaggar (Darton, 1901, p. 180) for 30-60 feet of pink- to red- or purple-colored carbonate, shale and silty beds in the basal part of the Mississippian exposed in the Black Hills.

The Englewood can be recognized as a reddish-colored zone in the basal Mississippian section in part of the adjoining surface area west and north. In Spearfish Canyon, where the thickness is about 40 feet, the rocks are dove-colored, slabby carbonates with purplish concretions, merging upward into purplish-gray shales.

The type section is near Englewood Station south of Lead, South Dakota. The character of the formation varies in different parts of the Black Hills. Near the town of Deadwood, the Englewood consists of dark gray or dark purple-gray shale, containing Mississippian graptolites (Ruedemann and Lochman, 1942, p. 658). Darton (1909, p. 20) reported that the fauna in this formation represents an early stage of the Mississippian (his lower Carboniferous series) and may be correlated with the Chouteau Limestone of Missouri.

Foster (1960) on the basis of his study of the Devonian section exposed along the U.S. Highway 14 roadcut (north bank of Little Tongue River) on the east flank of the Big Horn Mountains, near Dayton, Wyoming, stated that "The section as a whole has a very distinctive light reddish-purple color suggestive of the Englewood Formation in the Black Hills." He also suggested that the Englewood, as a possible correlative of the Highway 14 Devonian section, should be examined for conodonts.

Klapper and Furnish (1962, p. 2073) suggested on the basis of conodonts that "the fauna in the middle part of the Englewood (10-34 feet below top) at Boxelder Canyon is regarded as late upper Devonian." He also stated that "The fauna from the top 10 feet of the Englewood and from the basal three feet of the Pahasapa at Boxelder Canyon and from the top two feet of the Englewood and the basal six feet of the Pahasapa at Whitewood Canyon is definitely lower Mississippian."

2. Mississippian Rocks: The Mississippian system is more widespread in distribution than any of the underlying Paleozoic systems in the study area.

The Mississippian rocks are divided into two formations: These are:

1. Englewood Formation (at the base)
2. Pahasapa Formation

The Englewood Formation was discussed under the previous section.

Pahasapa Limestone - Darton (1905) first described the Pahasapa Limestone. He first applied the name Pahasapa to ridge-forming light gray limestone in the Black Hills area, South Dakota and adjoining Wyoming. The light gray carbonates of the Pahasapa crop out and encircle the central part of the Black Hills uplift. It presents great cliffs for many miles along Spearfish Canyon and many other canyons, including those of the Whitewood, Bear Butte, Elk, Little Elk, Boulder, Rapid, French, Hell, West Fork of Lighting, False Bottom, and little Spearfish creeks. The outcrop encircles Crow Peak, Citadel Rock, Whitewood Peak, and Deadman Mountain, and it constitutes an uplifted block on the east side of Bear Butte. It is brought up in the Crook Mountain dome and by the anticline crossed by Bear Butte Creek four miles southwest of Sturgis.

The Pahasapa Formation has a conformable relationship with the underlying Englewood (Fig. 9A and B), and an unconformable contact with the overlying Minnelusa Formation.

The thickness of the Pahasapa varies widely ranging from 500 feet determined by the writer measured in Spearfish Canyon to a minimum of 100 feet on the flanks of Pole Mountain as reported by Jaggar. According to Jaggar (in Darton, 1901, p. 509), the thickness increases toward the south, reaching 300 feet in Whitewood Canyon, 500 feet in Bear Butte Canyon, and 600 feet or more on Bear

Fig. 9A. Photograph showing the contact between the Pahasapa Limestone and the Englewood Formation. Note the distinctive color of Englewood which is pale pinkish. Iron Creek locality.

Fig. 9B. Photograph showing the contact between the Pahasapa Limestone and the Englewood Formation. It also shows the contact between Englewood and Whitewood Formations. Little Spearfish locality.

Pahasapa

Englewood

Fig. 9A

Pahasapa

Englewood

- - - -

Whitewood

Fig. 9B

Butte Creek and Elk Creek. The Pahasapa is characterized by many solution cavities and caverns (Fig. 10). All the commercially developed caves in the Black Hills - Wind, Crystal, Jewel, Onyx, Rushmore and others - are in the Pahasapa.

It is also known that the Pahasapa crops out throughout a large area which extends from South Dakota to Montana and Wyoming. In the subsurface the Pahasapa carbonate is equivalent to a large part of the Madison Group of early and late Mississippian age, which in places is subdivided into the Lodgepole and Mission Canyon Limestones and the Charles Formation. The Madison Group is as much as 1,200 feet thick in the very northwestern South Dakota, but thins to the south and east toward the Black Hills outcrop area (Gries and Mickelson, 1964, pp. 109-118; see also isopach map in Fig. 19).

D - Pennsylvanian and Permian Rocks

Minnelusa Formation - The Pennsylvanian and Permian Minnelusa Formation unconformably overlies the Pahasapa, and in the subsurface, as F. A. Swenson reported (1968, p. 168), it overlies the Madison or the Kibbey Sandstone, the Kibbey occurring in the extreme northwestern part of South Dakota. The Minnelusa has much the same outcrop area as the Pahasapa. It is largely a massive sandstone, but also includes limestone and dolomite beds, especially in its middle and lower parts.

In exposures, the Minnelusa Formation ranges in thickness from 300 feet to 850 feet. The Minnelusa Formation thins rapidly toward the east, in part as a result of pre-Jurassic and also pre-Cretaceous erosion. Unconformably overlying the Minnelusa are about 1,500 feet

Fig. 10A. and 10B. These photographs illustrate the cave development in the Pahasapa. The upper 125 to 150 feet of the Pahasapa Formation is very cavernous, and is locally referred to as the "cave" zone. This solution zone in which the caves occur appears to be related to pre-Minnelusa erosion and solution surface rather than to any lithologic unit within the Pahasapa Formation, according to Gries (1964). Iron Creek and Deadwood localities, respectively.

Fig. 10A

Fig. 10B

of Permian, Triassic, and Jurassic sedimentary rocks. These strata are largely shale, but include some beds of sandstone and limestone.

Table 1 contains the Pennsylvanian, Mississippian, Devonian and Ordovician nomenclature of the Black Hills, South Dakota.

TABLE 1

PENNSYLVANIAN, MISSISSIPPIAN, DEVONIAN, AND ORDOVICIAN NOMENCLATURE OF THE BLACK HILLS, SOUTH DAKOTA

System	Series	Formation	Thickness In Feet	Character of Beds
Pennsylvanian		Minnelusa Fm.	650-800	Light-gray and red sandstone, gray limestone and dolomite, red shale, local gypsum and anhydrite
		Unconformity		
Mississippian	Osagean	Pahasapa Fm.	500-600	Light-gray limestone, locally dolomitic and dolomite
	Kinderhookian			
Devonian		Englewood Fm.	50-60	Pink or purplish-gray - thin bedded limestone; or dolomite; locally argillaceous
		Unconformity		
Ordovician	Upper Ordovician	Whitewood Dolomite	50-60	Mottled grayish-yellow, massively bedded, limestone and dolomite
	Middle Ordovician	Winnipeg Fm.	60-70	Upper part greenish-gray siltstone. Lower part greenish-gray shale

PETROGRAPHIC CONSTITUENTS OF CARBONATE ROCKS

A - Introduction

Since 1870 when Sorby's definitive paper dealing with carbonate rocks appeared, many classifications have been introduced. However, because of the complexity of carbonate rocks, no single classification satisfies the needs of every user.

Folk's classification (1959) was an important advance in carbonate petrography. It enables the carbonate petrographer to describe as well as understand genesis better. His classification deals largely with limestone, both recent and ancient in origin.

Folk's classification has been successfully applied in recent years because of its emphasis on petrographic character and the fact that it combines both descriptive and genetic factors.

In the rock descriptions in this study the classification and terminology of Folk (1959) has been adopted, but with some modification because the rocks that were studied have undergone sufficient recrystallization so that his basic classification cannot be readily utilized. For diagenetic fabrics, the terminology employed follows that of Schmidt (1965, p. 128).

In his scheme of classification of limestone, Folk (1962, pp. 62-84) utilized texture as an important parameter. In his classification, Folk establishes and defines three end members which in varying amounts make up most limestones:

1. Allochems
2. Microcrystalline calcite, "micrite"

(deposited as an ooze)

3. Sparry calcite

The following discussion explains the different kind of carbonate constituents; they are not necessarily found in the rocks studied in this project, but are briefly discussed here as a necessary introduction to the terms used in this study.

B - Allochemical Constituents

Folk proposed the term "allochem". The term is defined as carbonate particles that are transported within the basin of deposition. Folk explains that allochem are not ordinary chemical precipitates, but are complexes that have achieved a higher degree of organization and, in nearly all cases, have also undergone transportation.

As pointed by Folk, only four allochem types are volumetrically important in limestones. These four are:

1. Intraclasts
2. Oolites
3. Fossils
4. Pellets

They are briefly discussed below:

1. Intraclasts - Intraclasts, as defined by Folk (1959, p. 4) and used by Folk and Bissell (1967, p. 159), are fragments of generally weakly consolidated carbonate sediment that have been eroded from adjoining parts of the sea bottom and redeposited to form a new sediment. The particles have been reworked within

the area of deposition and usually within the same formation. The intraclasts are usually composed of microcrystalline calcite without internal structure; some show the effect of abrasion; others have irregular boundaries which are attributable to the deformation of weakly cohesive lime mud. Intraclasts range from very find sand size to pebble or boulder size. The origin of intraclasts are multiple but at least three modes of formations are postulated in the literature:

a. Breaking down of pre-existing consolidated limestone into rock fragments generally referred to as lithoclasts and phenoclasts.

b. Penecontemporaneous reworking of recently lithified or partly consolidated carbonate mud (Folk, 1959, p. 4). Such intraclasts could be formed by storm action, where erosion of older, deeper layers of semi-consolidated lime mud takes place down to several feet below the sea bottom, followed by reworking and subsequent deposition on shallow water.

c. Subaqueous aggregation of loose carbonate mud has been shown to play a role in forming some intraclasts (Illing, 1954, p. 26). Illing suggested the name grapestone for calcareous particles which cemented together into lumps. Beales (1958, p. 1846) suggested the term bahamite for intraclasts of similar origin. The environmental implication of this type of intraclasts are significant; they are formed without reworking of previously deposited lime mud.

Folk (1962, p. 64) reported that the bahamites or grapestones of Illing and Beales seem to be the most important type of intraclasts forming in modern limestone environments; but, this, according to the same observer (Folk) was by no means true throughout much of the Paleozoic or Mesozoic. Folk firmly stated that intraclasts should be used as a broad class term without specifying the precise origin. Folk suggested the terms bahamite and grapestone to be used for specific type of intraclast if the particles have bumpy outer surfaces and look like little-abraded pellet aggregates.

2. Oolites - Oolites are spherical allochems which have either radial or concentric internal structure or both. These structures usually surround nuclei which may consist of shell fragments, quartz grains, pellets or any grain small enough to be rolled by currents.

   The mode of origin and occurrence of oolitic rocks have been described by Newell, Purdy, and Imbrie (1960, p. 492), Baars (1963, pp. 113-114), discussing the depositional environment of oolites, considered that they form only in shallow water (six feet deep or less), where the bottom sediments are in either constant or intermittent motion, and oolite shoals or bars are generally restricted to shelf margin environment.

3. Pellets - Pellets are small, ovoid or elongate bodies that are roughly equidimensional and, in turn, composed essentially of micrite. The pellets may be of silt- to sand-size. As pointed out by Baars (1963, p. 105) and Leighton and Pendexter (1962, p. 36),

pellets may be faecal debris or grains of micrite. Baars (1963, p. 107), reported that some carbonate particles may be coated by algal processes. The origin of pellets has been discussed by many workers and it is agreed that they are of multiple origin, being formed as (a) faecal pellets (Illing, 1954, p. 24) (Ginsburg, 1957, p. 81), (b) algal pellets provided by the abrasion of algal debris (Wolf, 1965, p. 141); (Beales, 1958, pp. 1856-1857). Pellets may be deposited on banks, shelves, and lagoons particularly in warm climatic zones.

4. Fossils - The petrography of fossil remains are important in the study of carbonate rocks. The geological literature dealing with topic is not large and includes the classical work of Cayeux (1916), Bogglid (1930), and Johnson (1951).

C - Microcrystalline Calcite, "Micrite"

Micrite, as defined by Folk (1959, p. 8), is a chemical precipitate formed of grains four microns (0.004 mm.) or less in size. Leighton and Pendexter (1962, p. 35) defined the micritic material as that consisting of particles less than approximately 0.03 mm. in diameter. In this study, the writer applied the term micrite for material, whether crystalline or finely grained which is 0.001 to 0.004 mm. in diameter and dolomicrite to dolomite crystals or grains of the above mentioned size. Under the petrographic microscope, it appears generally gray in color and consists entirely of microcrystalline calcite. Micritic rock is composed of 90 percent or more microcrystalline calcite.

The origin of microcrystalline calcite has been attributed to the following process:

a. Rapid chemical and biochemical precipitation in sea water (Newell and Rigby, 1957, p. 59).

b. Organic, from calcareous algae (Lowenstam, 1955, pp. 270-272). He noted that the mud-size aragonite needles in the Great Bahama Bank may be derived from calcareous algae.

c. Physical and biological abrasion of skeletal debris forming clay- or silt-size matter (Folk, 1959, p. 8).

d. Precipitation of aragonite needles in shallow marine water and later inversion to calcite (Illing, 1954, p. 16; Newell and Rigby, 1957, p. 59).

However, most investigators regard the source of microcrystalline calcite as a combination of organic processes and physiochemical precipitation.

D - Sparry Calcite Cement

Folk (1959, p. 8), referred to sparry calcite cement which forms grains or crystals 10 micron or more in diameter. The name spar alludes to its relative clarity both in thin sections and hand specimen.

There are two types of sparry calcite: (a) an original precipitate, the drusy mosaic of Bathurst (1958, p. 14) or void filling calcite of Harbaugh (1961, p. 191), and granular cement, rim cementation of Bathurst (1958, p. 21), or (b) sparry calcite that has been formed by the "recrystallization" of microcrystalline calcite or fine carbonate mud.

DOLOMITE

A - Introduction

In this study, the writer would like to emphasize the dolomites and dolomite problems since most of the Pahasapa is dolomite in the thesis area. Dolomites have been defined as carbonate rocks composed of the mineral dolomite. As pointed out by Pettijohn (1957, p. 416), despite the possible ambiguity arising from the use of the same term (dolomite) for both the mineral and the rock, this term will probably continue to be used for both. Dolomites, especially finer grained dolomites, are quite similar to limestones in appearance and, therefore, it is difficult to distinguish between the two with the naked eye.

Before discussing the petrography and classification of Pahasapa carbonates, it is important that attention should be directed to some of the prevailing concepts regarding types of dolomites. For example, Vishnyakev (1951, p. 112) recognized the following major genetic types:

1. Epigenetic - Vishnyakev considered those dolomites as epigenetic which resulted from the alteration of completely lithified limestone either by downward percolating meteoric solution or by rising hydrothermal solutions, mainly along fractures. These dolomites have obscure stratification, patchy distribution, nonuniform grain size, relict structures, and are cavernous (Chilingar, 1967, p. 108).

2. Diagenetic - These dolomite originate shortly after the deposition of the original carbonate. They are those of great extent and volume. Fossil relicts are commonly present in diagenetic dolomites.

3. Primary - Primary dolomites result from direct chemical precipitation from sea water, and they lack appreciable porosity, are normally dense, and are commonly interlayered with evaporites, clays, marls, micrite with suspended oolites.

Teodorovich (1958, p. 303) does not believe in very widespread occurrence of epigenetic dolomites because of the difficulty in explaining the source of huge amounts of magnesium which is necessary to effect dolomitization.

Carbonate Terminology Used in This Thesis:

In the rock descriptions in this study the classification and terminology of Folk (1959, p. 14) has been adopted. Also for diagenetic dolomite, the terminology of Schmidt (1965, p. 128) was used with slight modification. Table 2 includes the descriptions of the rock types encountered in this study.

The rocks of the Pahasapa Formation are divided into eight rock types as follows:

1. Dolosparite - Dolomite that is more than 90 percent dolomitic spar.

2. Biodolosparite - Or dolomitic sparry allochem. The dolomite consists of 10 to 50 percent allochems, mainly fossils, and dolomitic sparry calcite cement.

3. Crinoidal biodolosparite - As above but the allochems are mostly crinoid remains.

4. Biodolomicrite - This is dolomitized allomicrite

TABLE 2

SUMMARY OF ROCK TYPES AND ENVIRONMENTS OF THE MISSISSIPPIAN PAHASAPA CARBONATE ROCKS IN THE NORTHEASTERN QUADRANT OF THE BLACK HILLS, SOUTH DAKOTA

Present Rock Type	Description or Lithology	Inferred Limestone Type Before Dolomitization	Original Constituents	Environment
Dolosparite	These rocks are composed of clear dolomitized spar crystals having a crystal size no smaller than 10 microns.	Sparite	After deposition of calcite ooze, the mud was eventually recrystallized to sparry calcite.	Low energy in shallow marine water.
Biodolosparite	Dolosparite containing more than 25 percent skeletal materials and fossil fragments. Commonly composed of many different skeletal types, randomly scattered throughout the rock.	Biosparite	Biomicrite. Recrystallization and void-filling later produced the sparry rock.	High energy shallow water relatively near shore. The diversified nature of the fossil assemblage suggests an environment in which all forms represented by the skeletal elements, flourished.

TABLE 2 Cont'd.

Present Rock Type	Description or Lithology	Inferred Limestone Type Before Dolomitization	Original Constituents	Environment
Dolobiomicrite	Dolomicrite with skeletal debris varying from 10-30 percent.	Biomicrite	Skeletal elements in a micrite matrix.	Low energy shallow water environment. The types of skeletal elements scattered throughout the dolomicrite matrix suggests the shallow water origin.
Dolomicrite	Microcrystalline dolomite often associated with pyrite and with less than 10 percent skeletal fragments.	Micrite	Micrite-produced by primary precipitation (as aragonite) from solution by chemical biochemical, or physiochemical processes.	Low energy, quiet water conditions.
Intrasparite	Sparry calcite with more than 20 percent intraclasts. The intraclasts are visually darker than the sparry calcite matrix.	Intrasparite	Micritic fragments were detached from a semiconsolidated rock and deposited as discrete limestone fragments.	This rock type is indicative of high energy conditions in the depositional environment, relatively near shore.

having 10 to 50 percent allochems and dolomitized microcrystalline calcite.

5. Dolomicrite - Having less than 10 percent allochems and more than 90 percent dolomitized microcrystalline calcite.

6. Sparite

7. Intrasparite - Like rock type No. 6 except here there are more than 20 percent intraclasts.

8. Dolointramicrite - Having less than 15 percent dolomitic intraclasts and more than 85 percent dolomitized micrite.

PETROGRAPHIC DESCRIPTIONS OF THE PAHASAPA CARBONATES

The following section describes the main rock types found in the Pahasapa carbonates at the study areas. These rock types are listed in order of their abundance in the formation.

A - Dolosparite and Biodolosparite (types 1 and 2)

These rocks are composed of dolomite spar. Dolosparite, which is the most common rock type in the Pahasapa, is made up of coarsely crystalline dolomite with up to 10 percent allochems; in places, argillaceous materials in excess of 10 percent are found. These latter constituents give the rock a gray to brownish color. Most of the dolospar crystals range in dimensions from 10 to 120 microns. These crystals are large, subhedral to anhedral and they produce a uniform mosaic. The allochems which make up this facies are skeletal fragments. These fossil fragments are very abundant in this rock type. They range in size from 0.1 mm. to over 3.0 mm., generally are poorly sorted and are abraded. Brachiopods, crinoid stems or columnals, and gastropods are abundant and well-preserved. Corals are numerous in these dolosparites (Plate 1). The internal cavities of the corallites are filled with dolospar. The dolospar is often in optical continuity with individual crinoid nuclei. Occasionally the crinoid columnals have been replaced with single crystals of dolomite spar. Other bioclastics are present, but are usually unidentifiable.

The microscopic aspects of fossils in common biodolosparite are

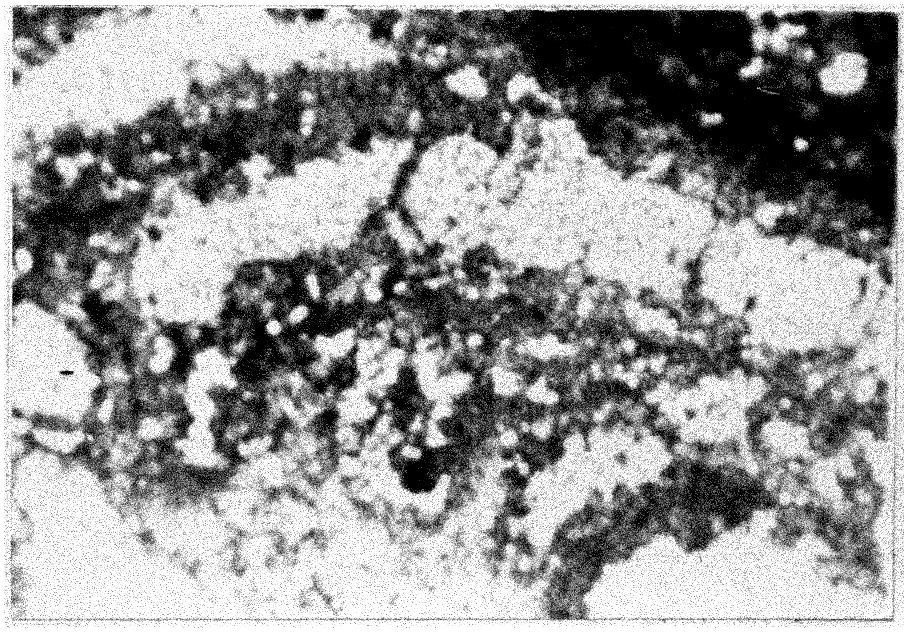


PLATE 1. PHOTOMICROGRAPH

This plate shows corallites of *Syringopora* filled with sparry calcite. Dolomitization has affected only the micrite between the corallites - where some crystals of dolomite were produced - but the corallite itself and the spar filling were not affected. x58.

discussed below:

Brachiopods - The shell structure of brachiopods is characterized by a thin, outer lamellar layer and a thicker, inner layer containing long slender dolomite prisms. The lamellar, outer layer is absent in some examples (Plate 2, Fig. 1).

Bryozoans - Due to dolomitization and destruction of these fossils, the writer could not differentiate between ramose and fenestrate bryozoans in the Pahasapa. The zooids of the bryozoans are filled with microcrystalline dolomite and calcite, sparry void-filling calcite, or euhedral dolomite crystals (Plate 2, Fig. 2).

Mollusks - The only mollusks the writer could recognize were gastropods. Pahasapa gastropod shells are composed of three layers, each composed of calcite or dolomite prisms arranged in a different orientation with respect to prisms in the other layers.

Other fossil fragments - Other organic remains occur in the rock in small amounts. However, because of lack of distinguishing structural features, recrystallization, abrasion or organic destruction, they could not be identified (Plate 2, Fig. 2).

B - Crinoidal Biodolosparite

This rock type is present only in upper part of the sections, where it forms a small ridge of gray coarsely crystalline dolomite. Crinoid plates are a conspicuous ingredient in this well-packed rock type and make up more than 25 percent of the rock, almost to the exclusion of other organic remains. Crinoid material in the Pahasapa consists mostly of individual stem plates and fragments of stem plates. In fact, crinoid calycies are almost non-existent. The

PLATE 2. PHOTOMICROGRAPHS

Fig. 1. This photomicrograph shows a portion of a large brachiopod shell. The matrix consists of coarsely crystalline calcite partially replaced by often cloudy dolomite. Cross-Nicols. x58.

Fig. 2. This photomicrograph consists of crinoid columnals, bryozoans, brachiopods, and other unidentified fossils. The calcite cement is slightly impure and of the void-filling type. The internal cavities of the crinoids and bryozoans are filled with dark calcite. x58.

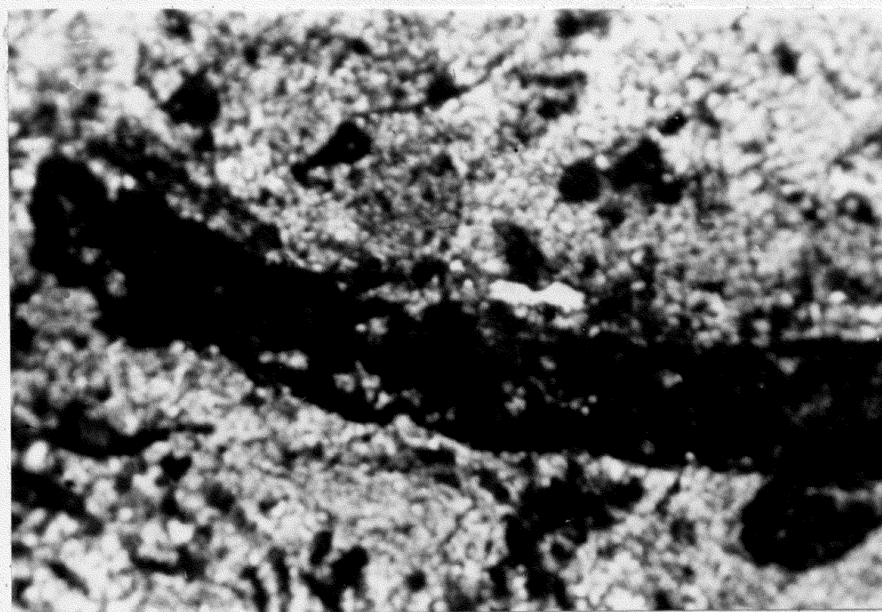


Fig. 1

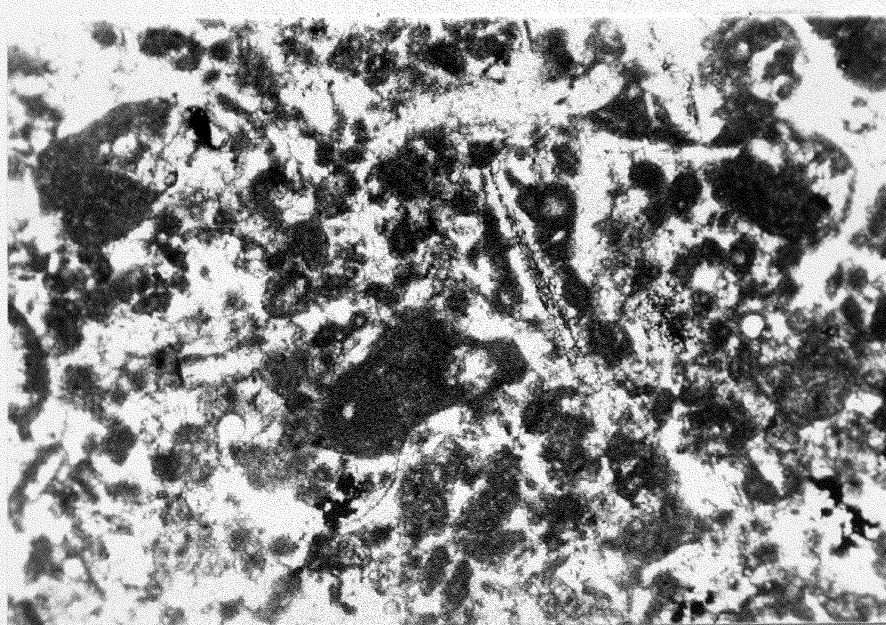


Fig. 2

PLATE 2

fragments appear well-worn, well-sorted and each plate is a single dolospar crystal. They are cemented together by overgrowth of dolomite spar which forms in optical continuity with each plate. This develops a coarsely crystalline texture in the entire rock. In thin sections the crinoids columnal can be distinguished from sparry dolomite by their central axial canal, but it is found to be essentially impossible to make distinction between crinoid and echinoid plates. Some of these crinoid plates are filled with brown fine-grained insoluble materials (Plate 3, Figures 1 and 2).

C - Biodolomicrite

This rock type is made up of a compact, occasionally mottled, well-bedded dolomite. This rock type displays some variation, and in places is composed partly of fossil fragments with small amounts of recrystallized dolomicrite forming biodolomicarenite. The suffix "arenite" attached to this rock type is to denote allochems of sand grain size; and "mic" to indicate the microcrystalline matrix. Fossil fragments constitute 15 to 20 percent of the biodolomicarenite; they are of sand grain size and consist primarily of gastropods, brachiopods, crinoids, and coral debris. Corals in growth positions, with internal cavities filled with calcite spar, are floating in dolomicrite matrix. Most of the fossils are commonly altered to a clear crystalline dolomite mosaic. Some fragments are partially or wholly replaced by dolomite.

D - Dolomicrite

This carbonate rock type is made up of very fine microcrystalline

PLATE 3. PHOTOMICROGRAPHS

Fig. 1. The photomicrograph shows a crinoid columnal in a sparry calcite matrix. Groove across columnal is a scratch. x58.

Fig. 2. The crinoid columnal in the center has been replaced with a few dolomite crystals. The clear area in the columnal are voids. The dolomite groundmass is medium to coarsely crystalline, often cloudy. It originated either by replacement of microspar or pseudospar or replacement of calcitic spar filling voids. x67.

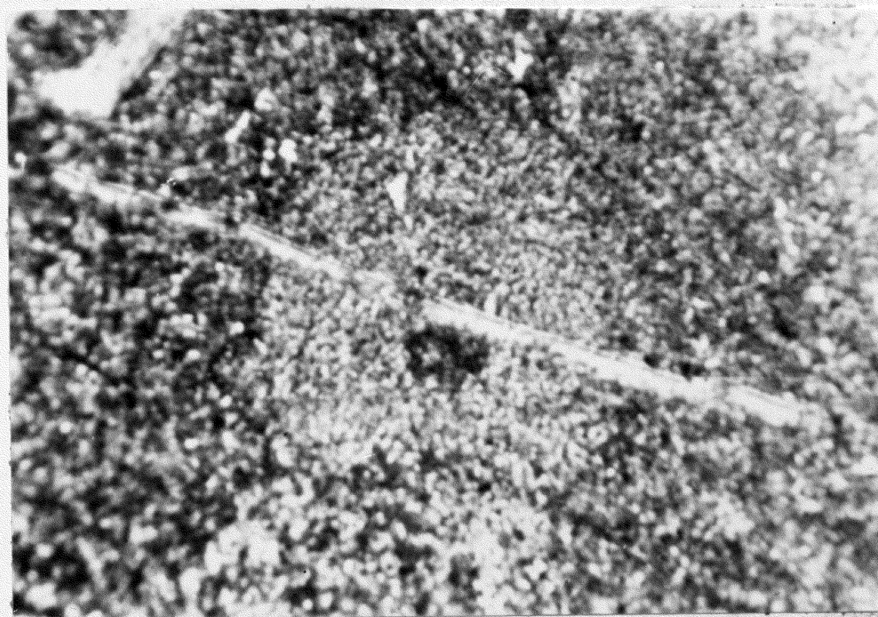


Fig. 1

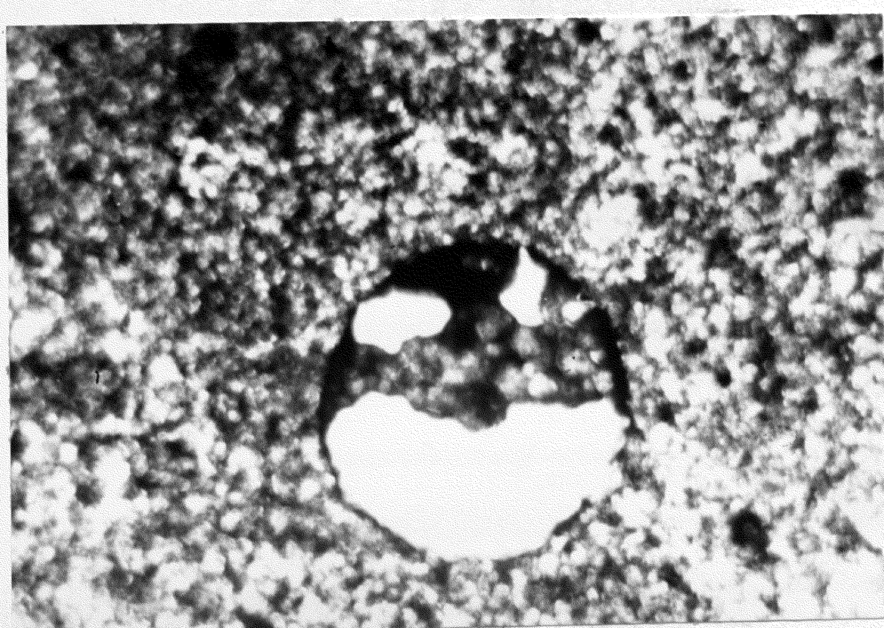


Fig. 2

PLATE 3

dolomite with less than 10 percent allochems. Little or no terrigenous quartz is found in it. The amount of dolomite in the micrite varies, with the dolomite crystals irregularly scattered through the micrite.

The dolomicrite is widespread in the section and may change laterally to biodolomicrite (Plate 4).

E - Intrasparite and Dolointramicrite

This rock type is not common. It is only found in one locality in the Bear Butte section. The intraclasts of this rock type (Plate 5, Fig. 1) are embedded in a coarse-grained microcrystalline dolomite, and they are composed mainly of micritic limestone which is petrographically identical to other micrite in the Pahasapa. The intraclasts vary in size from less than one inch to two inches, and they stand out prominently because of differential weathering between intraclasts and matrix.

The dolointramicrites are highly compacted, poorly sorted with angular to subangular dolointraclasts (Plate 5, Fig. 2). The intraclasts of the dolointramicrites rock types are dolomicritic in composition.

F - Terrigenous Quartz

Quartz of terrigenous origin, of silt and sand size, occurs in the dolospar and dolomicrite rock types in small amounts.

G - Authigenic Silica

Two kinds of authigenic silica were noted in the sections

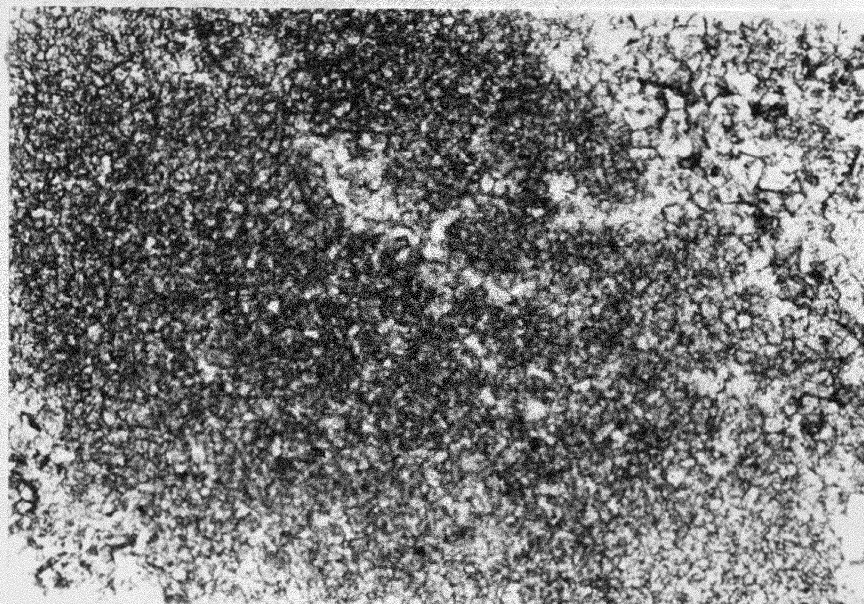


PLATE 4. PHOTOMICROGRAPH

The photomicrograph consists of homogeneous microcrystalline dolomite "dolomicrite" in which are scattered dolospar crystals. There are numerous large and clear calcite rhombs scattered at the right upper corner of the photograph. x58.

PLATE 5. PHOTOMICROGRAPHS

Fig. 1. Intraclasts of the Pahasapa Limestone in a matrix composed of fossil fragments and clear calcite crystals. The lithology of the intraclasts is identical to the composition of the previously deposited limestone. x58.

Fig. 2. Dolomitized intraclasts in a matrix composed of coarsely crystalline dolomite. The boundaries of the dolointraclasts are generally sharp. x58.

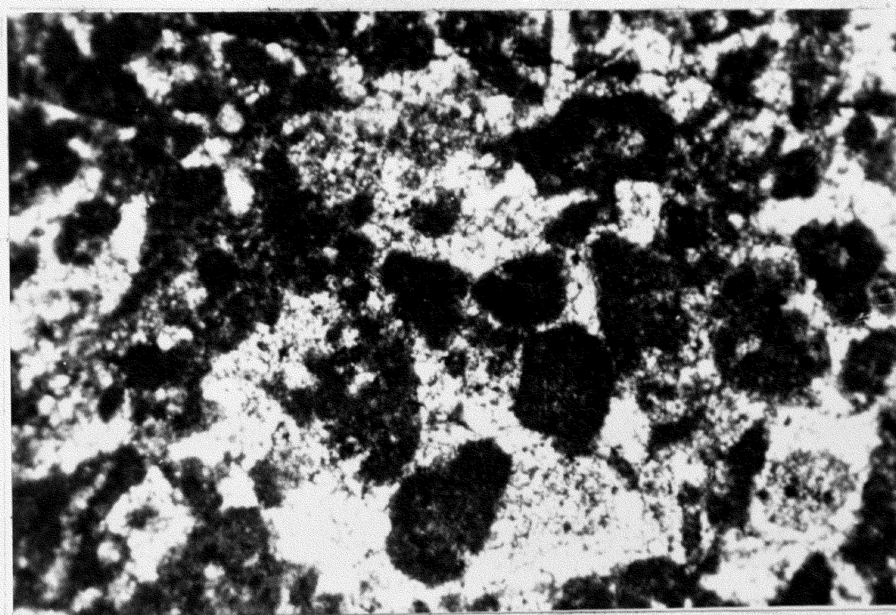


Fig. 1

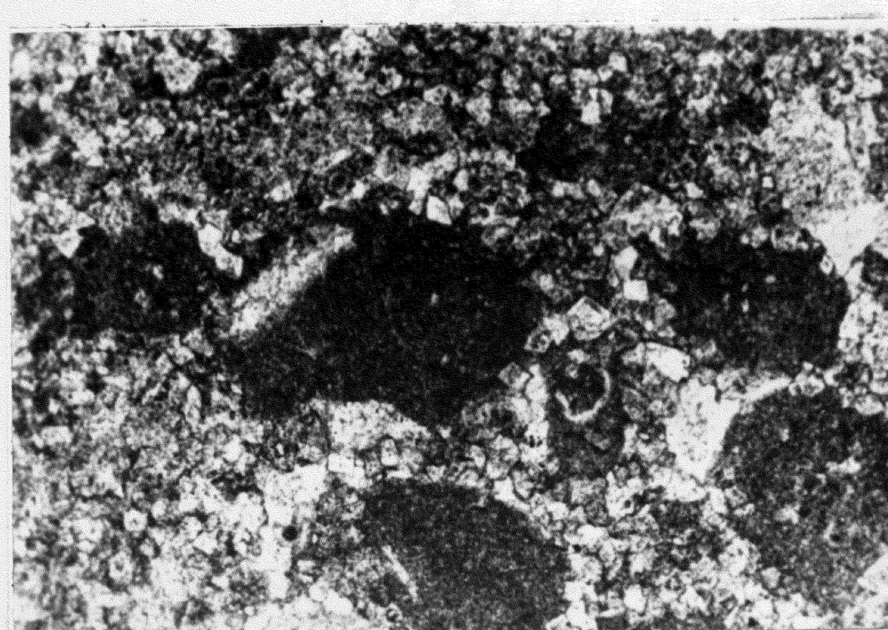


Fig. 2

PLATE 5

examined for this study; microquartz which makes up the chert and megaquartz which occurs as large quartz crystals (Plate 6) (Folk and Weaver, 1952).

1. <u>Microquartz</u> - Microquartz, also called chert, is quite common in the Pahasapa. In thin sections it is dark brown in color with many small irregular patches of calcite and dolomite. Chertified areas are subrounded to irregular in shape, granular in appearance. Microquartz in the Pahasapa consists of a mixture of microcrystalline quartz and chalcedonic quartz (as defined by Folk and Weaver, 1952). The grain size varies from 3 to 5 microns. The grains occurring in interlocking masses with more or less undulose extinction. The chalcedonic quartz displays a fiberous-aggregate structure under crossed nicols, the radiating fibers being only a few microns in diameter. Microcrystalline quartz is considered non-clastic.

2. <u>Megaquartz</u> - Megaquartz is coarse-grained, non-cherty authigenic quartz. It includes drusy quartz as well as overgrowth and authigenic quartz crystals. Megaquartz is not common in the Pahasapa; it occurs with dolomite veins as euhedral or subhedral crystals (Plate 6).

H - <u>Pore Space</u>

Pores in rocks have commonly been classed as either primary or secondary. Primary pores form early in the history of the rock,

PLATE 6. PHOTOMICROGRAPH

Large authigenic (megaquartz) quartz crystals in the center of this photomicrograph. The matrix is composed of finely to medium crystalline dolomite with abundant light calcite crystals. x58.

either during or shortly after deposition, or may occur later if they are created by fractures or solution. Modifications of pores that take place later are termed secondary. Examples of primary pore spaces include voids between individual crystals, voids between sand- and silt-size particles, voids along bedding planes, voids within a rigid framework provided by hard remains of organisms, and voids along joints and other fractures.

These pores may be grouped according to mode of occurrence. The principal modes are: (1) pores localized along small fractures, (2) pores within precipitate mosaics, and (3) pores localized at the contacts between skeletal particles.

Most of the pore structures in the Pahasapa carbonates are caused by dolomitization of limestone. Evidence for this is that most of the pore spaces are found where the dolomite occurs.

If pores, both associated with fractures and pores unassociated with fractures, had been observed in the same thin sections, their relative ages might have been determined. It is probable that pores unassociated with fractures (and due to recrystallization) formed earlier, perhaps before or during consolidation, whereas pores due to fractures formed later, presumably after consolidation was complete.

Pores in dolosparites and intrasparites are localized to some extent within the clear dolomite and calcite cement. It seems probable that incomplete filling of the original intergranular spaces by cement left pores that were later enlarged by solution.

Some of other pore spaces are characterized by a system of pores distributed between the grains and near the grains of the main mass of the dolomite rock, reflecting the outlines of the greatest part of these grains (intergranular pores). Other pores are like veinlets and are formed by fractures. Calcite in the veinlets is clear and consists of a mosaic of distinctly bounded anhedral grains (Plate 7). Some of these pores which are linear in shape contain crystals oriented perpendicular to the veinlet wall.

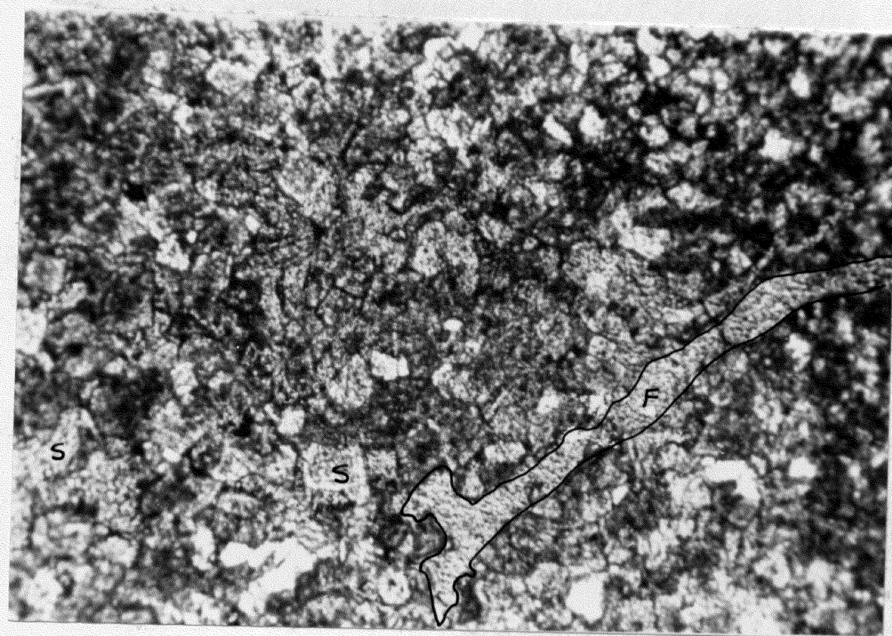


PLATE 7. PHOTOMICROGRAPH

Photomicrograph showing a fracture (F) which has been filled with spar (S). Such filled fractures are the predominant way in which the fractures occur in the Pahasapa. x58.

DEPOSITION AND ALTERATION OF LIMESTONE

A - Introduction

The Pahasapa carbonates are predominantly dolomites in the study areas. The rocks of this formation were classified in a previous section into eight rock types on the basis of their fabrics, variations in the texture, and types of fossils, are given again below:

1. Dolosparite
2. Biodolosparite
3. Crinoidal biodolosparite
4. Biodolomicrite
5. Dolomicrite
6. Sparite
7. Intrasparite
8. Dolointramicrite

The distribution of the above rock types are shown in the stratigraphic sections (Figures 11 to 17).

The following discussion will present possible courses of alteration of limestone which led to the type of dolomite listed above and also the environment of deposition based on the postulated petrographic character of the original limestone.

B - Alteration of the Pahasapa

1. Recrystallization - Recrystallization of either microcrystalline calcite or dolomite to coarser sparry calcite or sparry dolomite is a common phenomenon in the Pahasapa.

Fig. 11. Legend for the stratigraphic sections, and petrographic analysis, shown on bar diagrams for Figures 12 to 17.

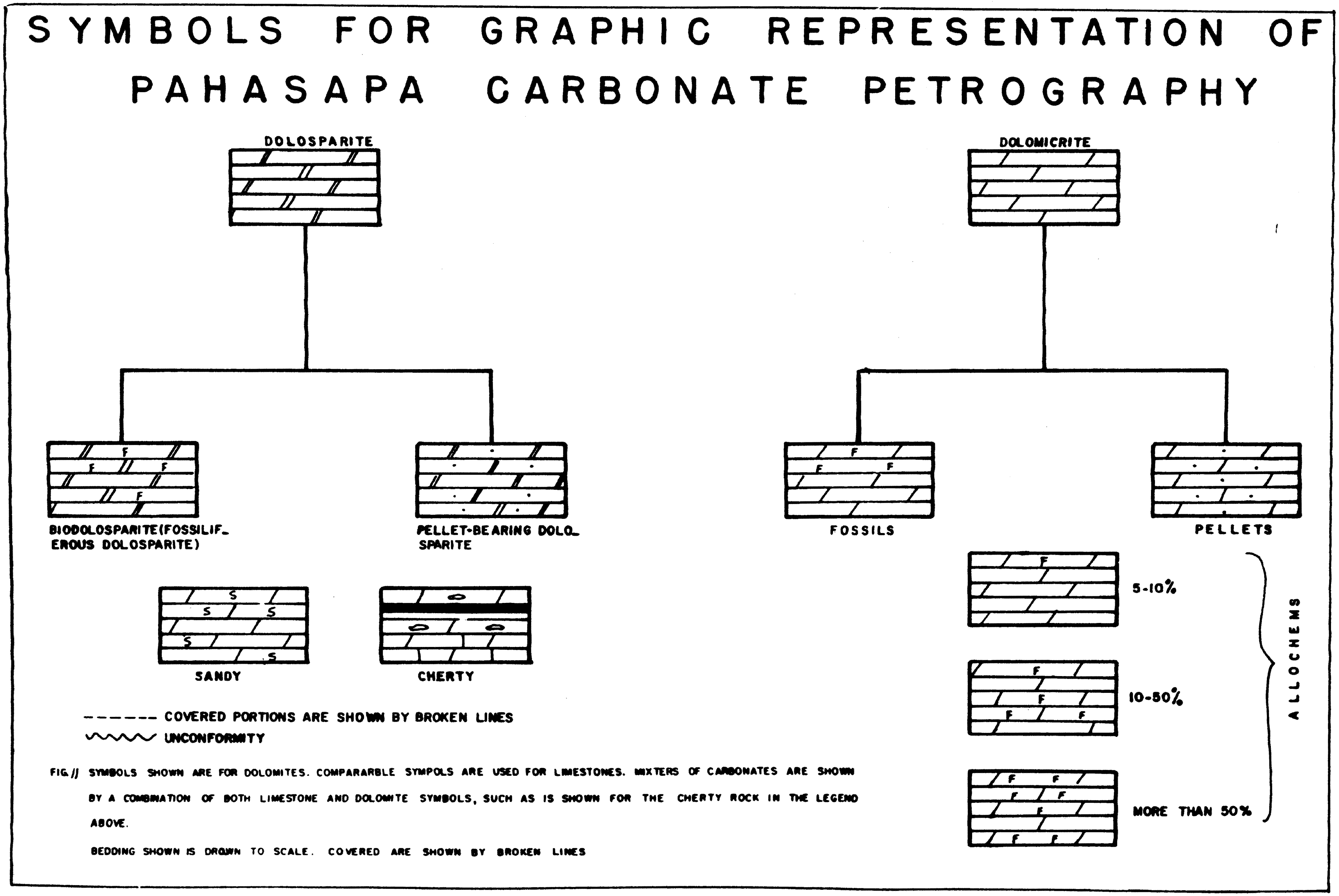

SYMBOLS FOR GRAPHIC REPRESENTATION OF
PAHASAPA CARBONATE PETROGRAPHY
DOLOSPARITE
DOLOMICRITE
BIODOLOSPARITE(FOSSILIF_
EROUS DOLOSPARITE)
PELLET-BEARING DOLO_
SPARITE
FOSSILS
PELLETS
SANDY
CHERTY
5-10%
10-50%
MORE THAN 50%
ALLOCHEMS
------ COVERED PORTIONS ARE SHOWN BY BROKEN LINES
UNCONFORMITY
FIG.// SYMBOLS SHOWN ARE FOR DOLOMITES. COMPARARBLE SYMPOLS ARE USED FOR LIMESTONES. MIXTERS OF CARBONATES ARE SHOWN
BY A COMBINATION OF BOTH LIMESTONE AND DOLOMITE SYMBOLS, SUCH AS IS SHOWN FOR THE CHERTY ROCK IN THE LEGEND
ABOVE.
BEDDING SHOWN IS DROWN TO SCALE. COVERED ARE SHOWN BY BROKEN LINES

Fig. 11

Fig. 12. Stratigraphic section at the Iron Creek locality. A more exact location is given on page 2. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.

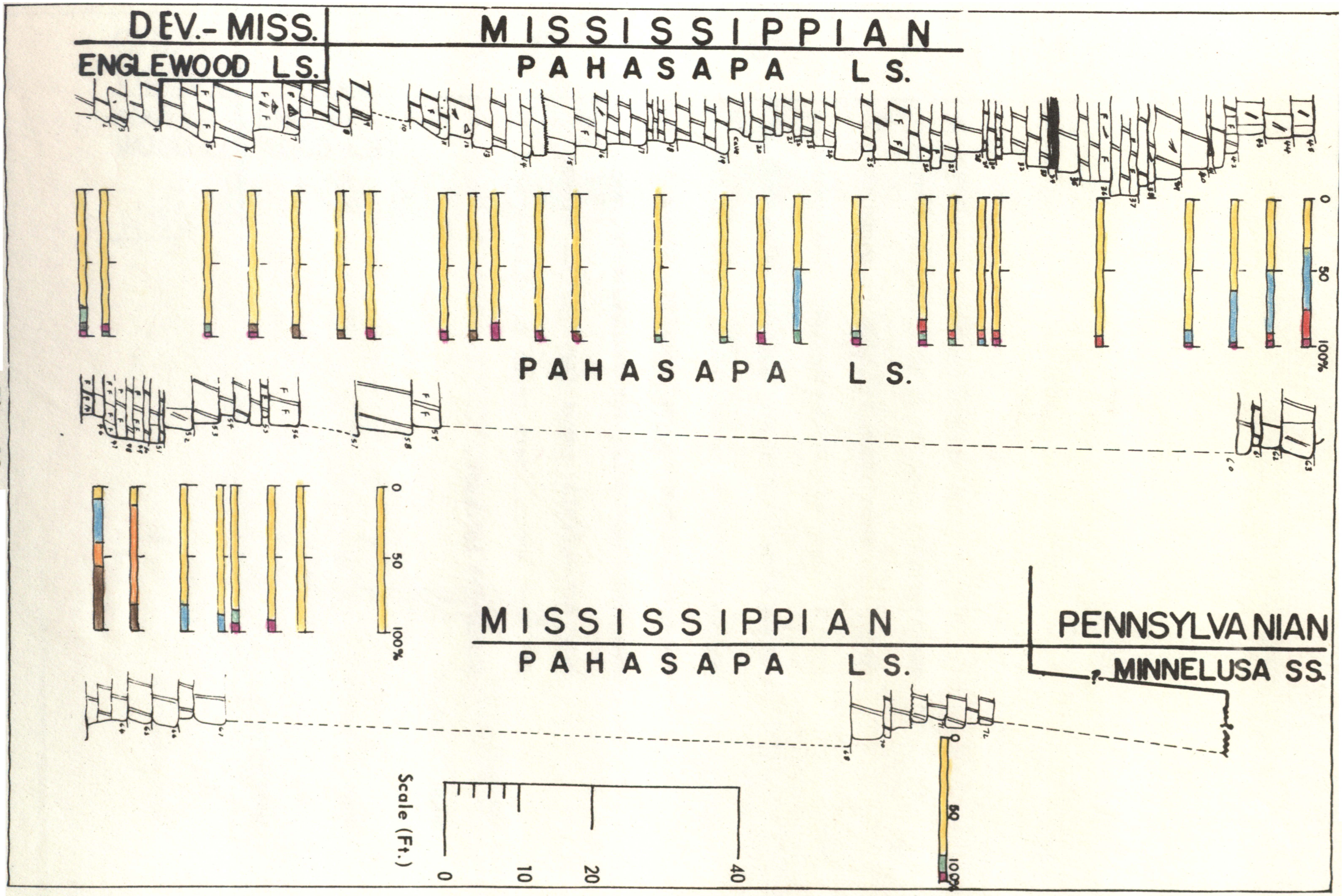
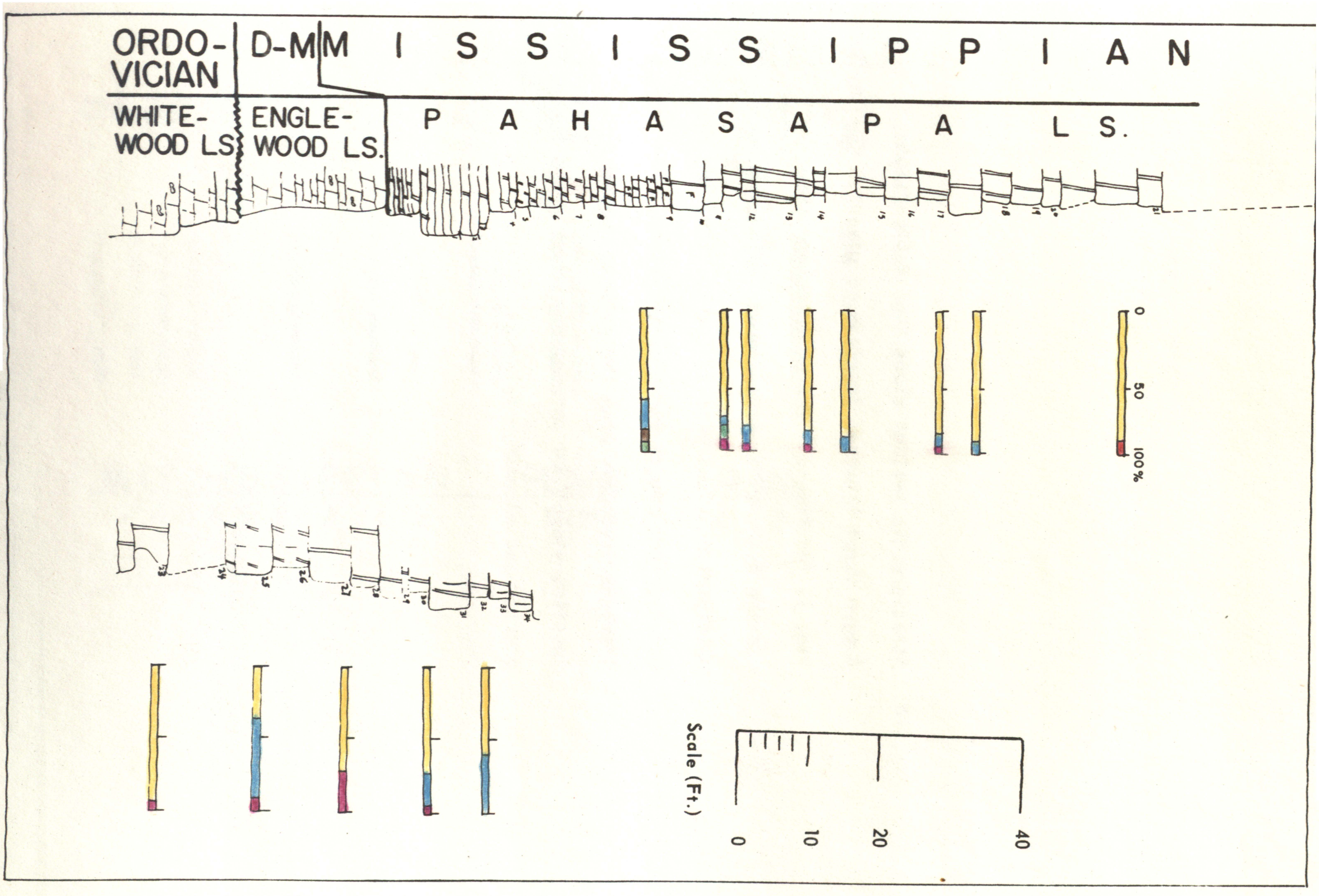

DEV.- MISS.
ENGLEWOOD LS.
MISSISSIPPIAN
PAHASAPA LS.
0
50
100%
PAHASAPA LS.
0
50
100%
MISSISSIPPIAN
PAHASAPA LS.
PENNSYLVANIAN
MINNELUSA SS.
0
50
100%
Scale (Ft.)
0
10
20
40

Fig. 12

Fig. 13. Stratigraphic section along Little Spearfish Canyon. A more exact location is given on page 2. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.



ORDO-VICIAN
D-M
MISSISSIPPIAN
WHITE-WOOD LS.
ENGLE-WOOD LS.
PAHASAPA LS.
0
50
100%
Scale (Ft.)
0
10
20
40

Fig. 13

Fig. 14. Stratigraphic section along Bear Butte Canyon. A more exact location is given on page 2. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.

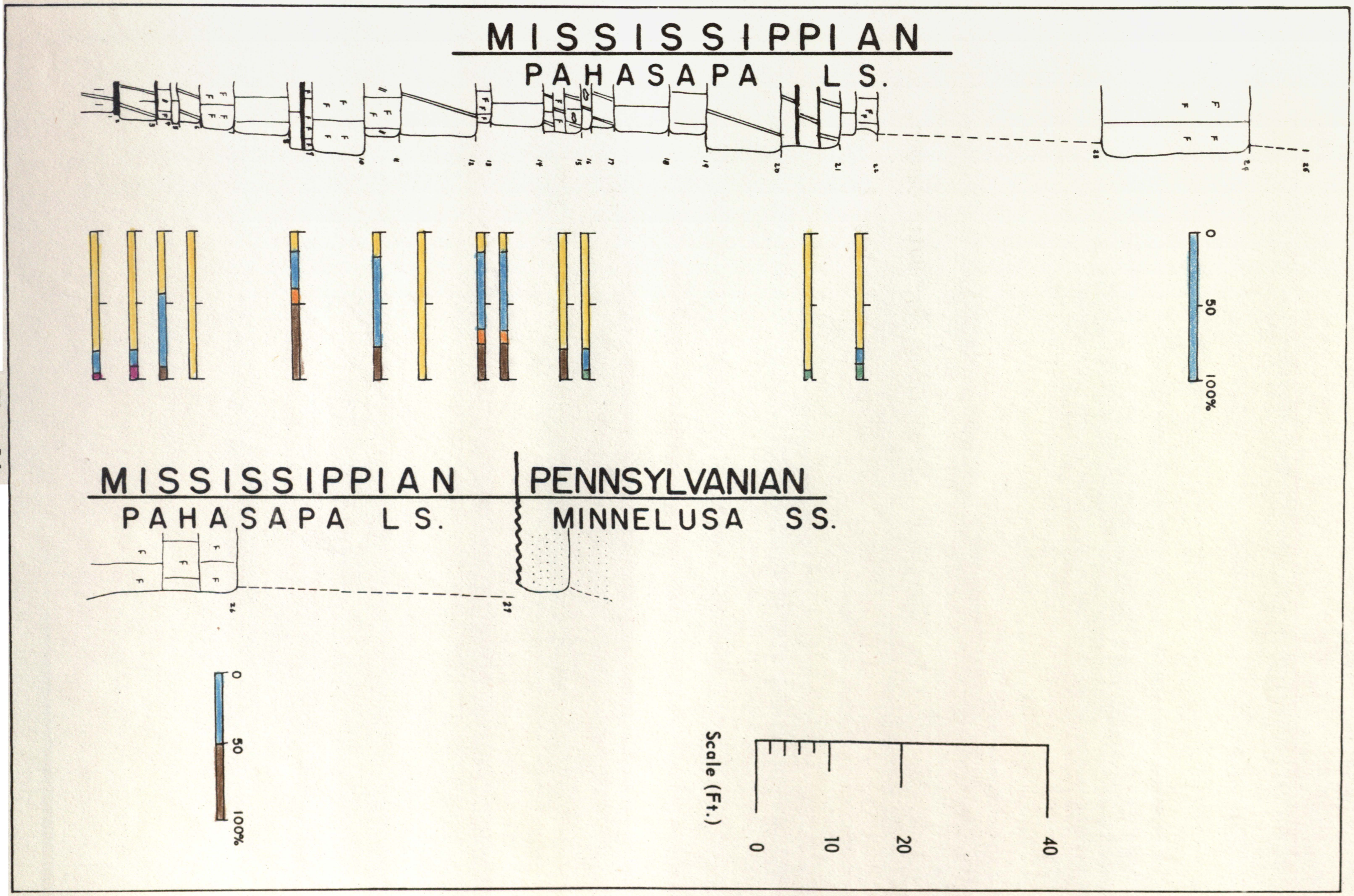

MISSISSIPPIAN
PAHASAPA LS.
0
50
100%
MISSISSIPPIAN
PAHASAPA LS.
PENNSYLVANIAN
MINNELUSA SS.
0
50
100%
Scale (Ft.)
0
10
20
40
Fig. 14

Fig. 15. Stratigraphic section at north side of Crow Peak. A more exact location is given on page 2. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.

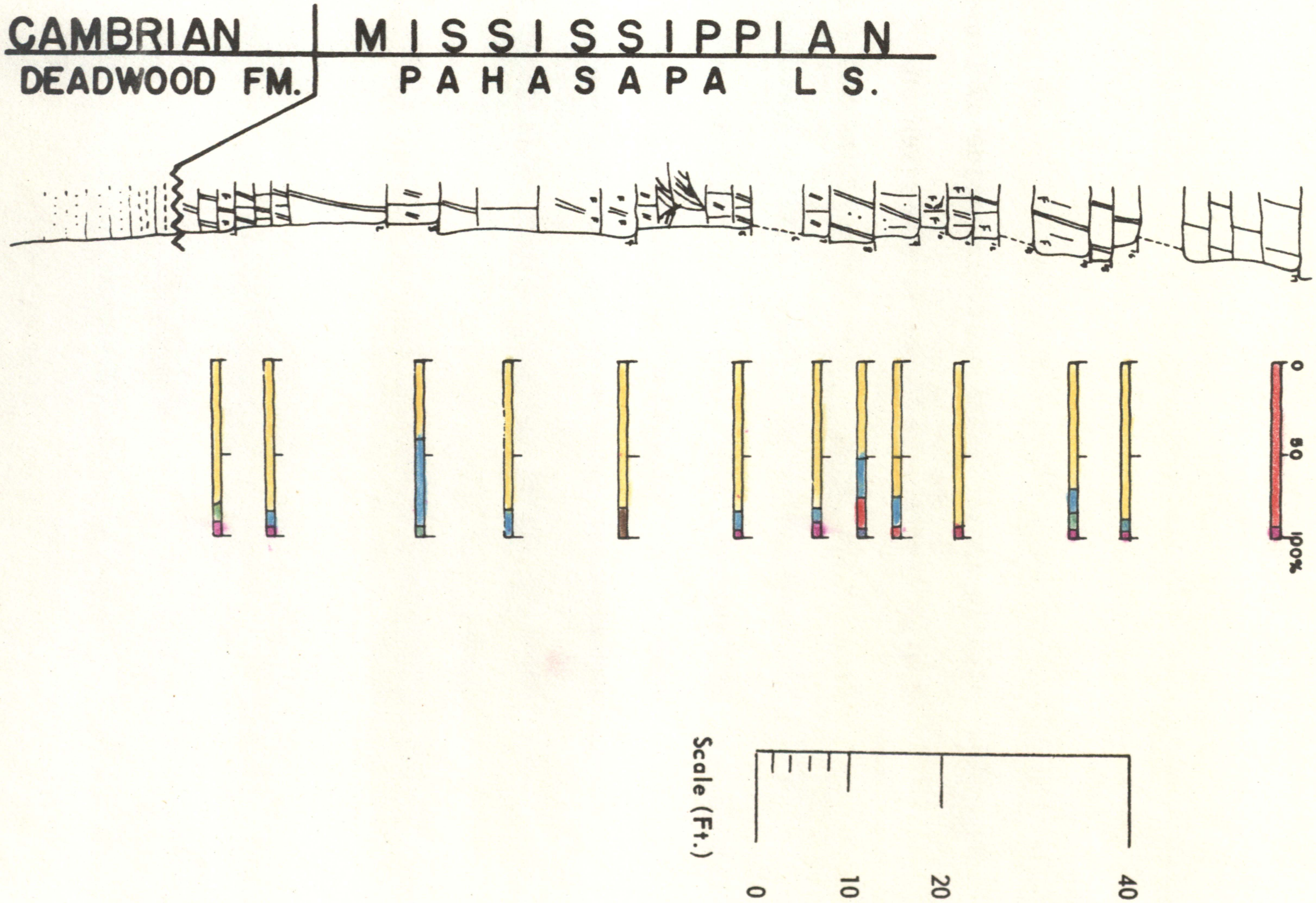

CAMBRIAN
MISSISSIPPIAN
DEADWOOD FM.
PAHASAPA LS.
0
50
100%
Scale (Ft.)
0
10
20
40

Fig. 15

Fig. 16. Stratigraphic section along Boulder Creek Canyon. A more specific location is given on page 2. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.

Fig. 16

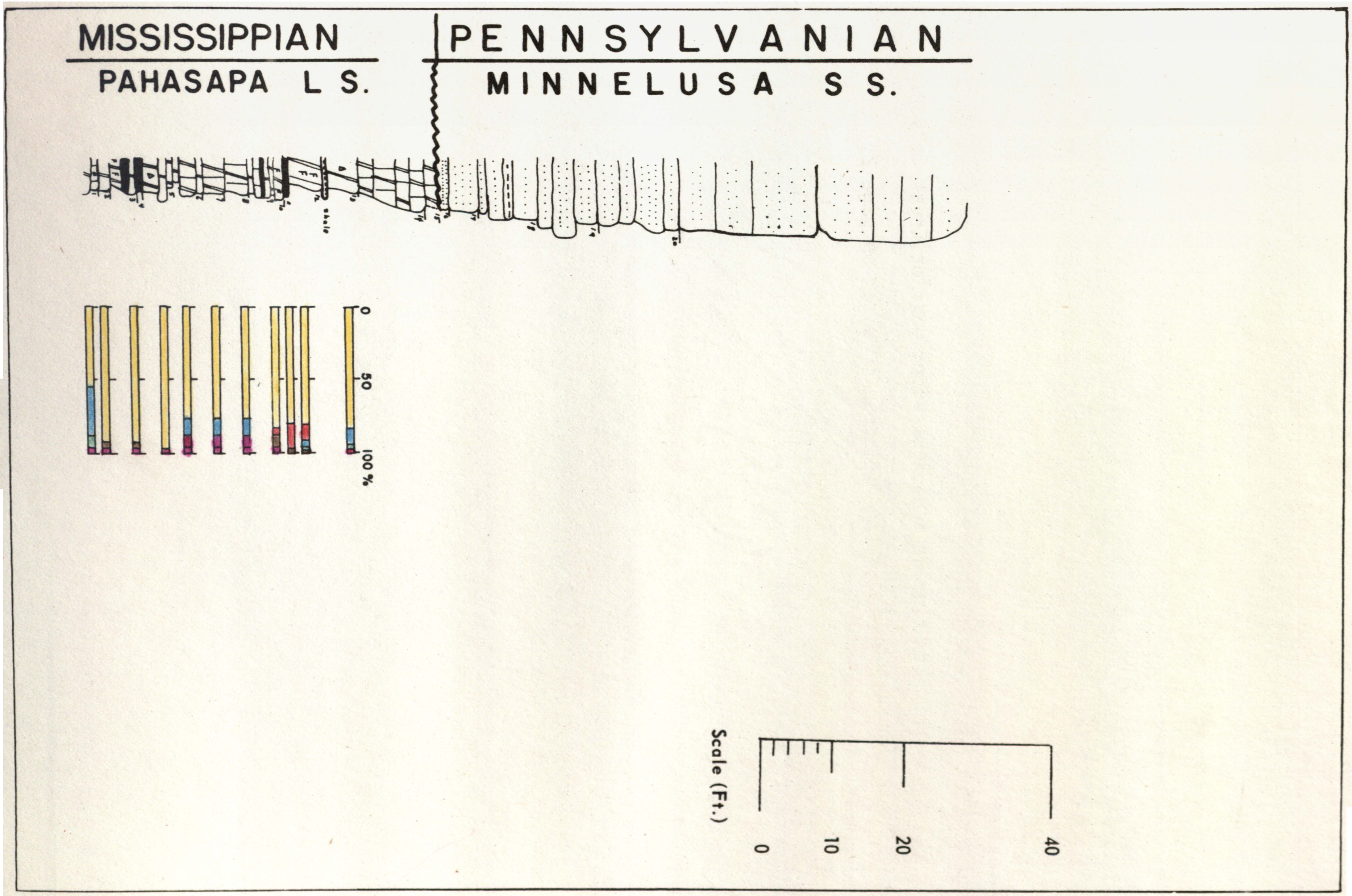

MISSISSIPPIAN
PAHASAPA L S.
PENNSYLVANIAN
MINNELUSA S S.
0
50
100 %
Scale (Ft.)
0
10
20
40

Fig. 17. Stratigraphic section measured at the Deadwood locality. A more specific location is given on page 3. See Fig. 11 for legend. The color scheme shown on the bar diagrams is as follows: yellow represents dolosparite, light blue is for sparite, red for dolomicrite, orange for micrite, light green for intrasparite, dark blue for pellets, brown for fossils, violet for pore spaces, dark green for quartz, and black for feldspar.

MISSISSIPPIAN
PAHASAPA LS.

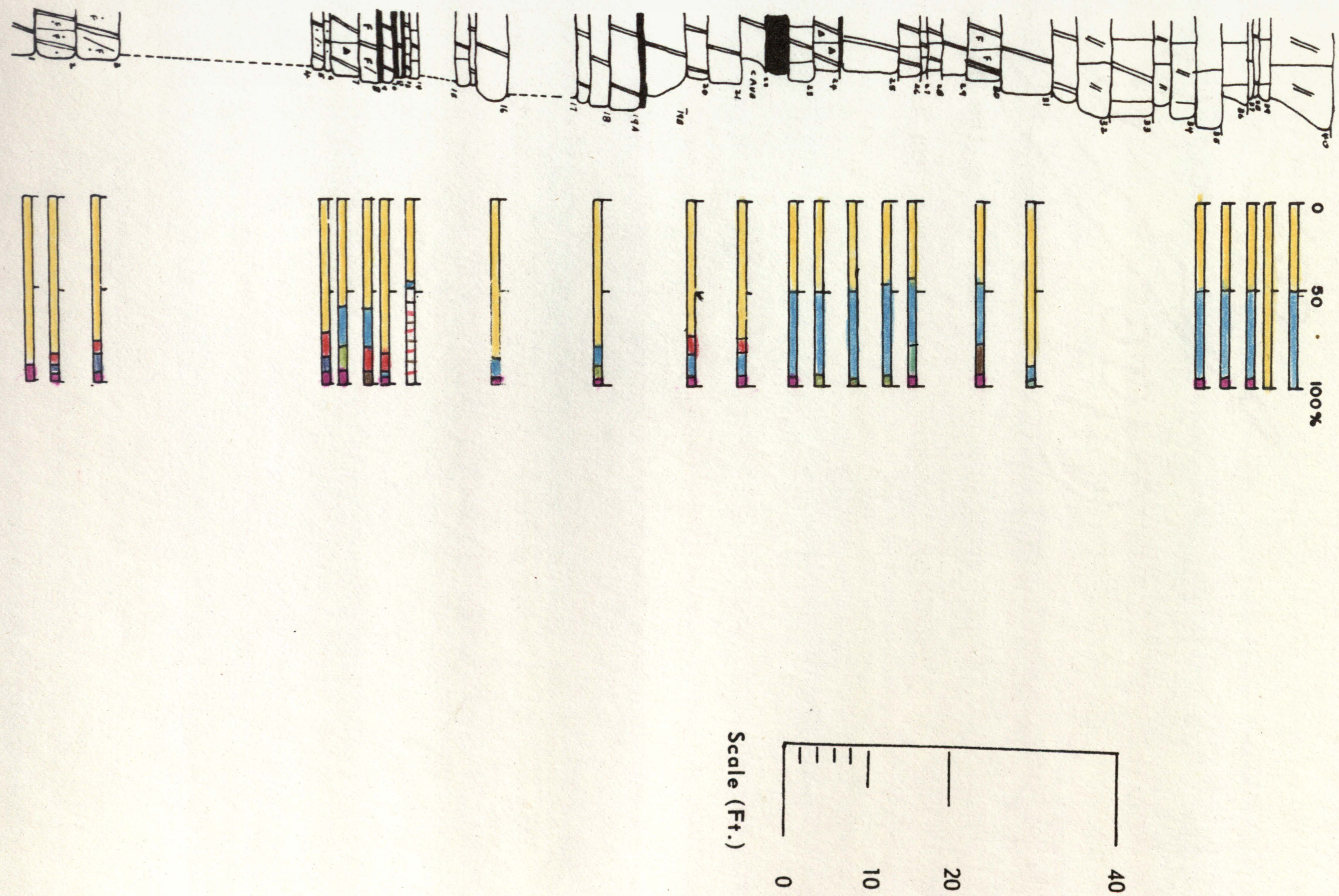


Fig. 17

The writer wants to clarify the use of the word recrystallization since there is much debate on the use of this term. The term recrystallization has been used loosely for a number of processes that commonly cause a change in crystal or grain size, predominantly an enlargement although occasionally a reduction in size, without causing a chemical alteration except for changes in isotope and trace element concentrations. Some prefer to include inversion and grain growth, whereas others prefer a restricted use of the term recrystallization. Bathurst (1958, p. 11) suggests that the term "recrystallization" be used only for changes of deformed to undeformed crystals and he used the term "grain growth" for the change of undeformed calcite to a new form and grain size. Folk (1965, p. 20), in a review paper considered inversion (where the mineral is replaced by its polymorph), recrystallization, and grain growth referrable to an all inclusive process which he terms "neomorphism".

In the sections studied in detail, about 80 percent of the original microcrystalline carbonate has been recrystallized to sparry carbonate with a wide range of crystal grain sizes. It includes both microdolosparite (5 to 15 microns) and macrodolosparite (15 microns and larger) as described by Folk for these neomorphic spar products. Evidence of recrystallization consists of progressive transition from microcrystalline carbonate to coarse sparry carbonate. Other strong evidence of recrystallization is provided by crinoid stems which originally consisted of monocrystalline calcite which now shows varying degrees of alteration of the calcite to dolomite (Plate 8, Fig. 1). Recrystallization of the rock involves both the groundmass and the fossils. Such complete recrystallization has also been described by Johnson (1957, p. 182). Characteristically, it starts in the groundmass and proceeds until most or all of the groundmass is replaced by coarsely crystalline calcite. Then the fossils are attacked from the outer edges or from cavities within the fossil (Plate 8, Fig. 2). First, crystals develop and grow along the margins of the shells and work forward in optical continuity into the groundmass. Gradually, the fossils become more and more indistinct until finally they are indicated only by marginal lines of "dust" color bands, or textured differences in the groundmass (Plate 9, Figures 1 and 2).

2. Spar development - Petrographers have differences of opinion regarding the origin of spar. To some workers, the formation of coarse sparry limestone is a function of metamorphism, and thus outside the realm of diagenesis. Grain growth and recrystallization, pressure-solution, syntaxial rim cementation, and drusy and fibrous spar cementation may work not only independently, but also in harmony with one another, to form sparry limestone from rock which was not originally a sparite (Chilingar, 1967, p. 281). Such processes are presumed to take place

PLATE 8. PHOTOMICROGRAPHS

Fig. 1. The elliptical object in the upper left is presumed to be a crinoid columnal. Dolomite (finer grained) has replaced a large portion of the columnal. Dolomitization has left an irregular contact at edge of the columnal. Crinoidal (and echinoderm) debris is the last fossil material to be dolomitized in the Pahasapa. The groundmass (fine grained) consists predominantly of dolomite. Light irregular patches donate matrix recrystallized to clear sparry calcite. Specimen No. 9 from Little Spearfish Canyon locality. x58.

Fig. 2. This photomicrograph illustrates the alteration of calcite spar to dolomite spar. The U-shaped area at the right is filled with calcite spar but at the edge large dolomite crystals have developed. The location and well-defined crystal boundaries support the suggestion that the dolomite replaced calcite. Specimen No. 53C from Iron Creek locality. x67.

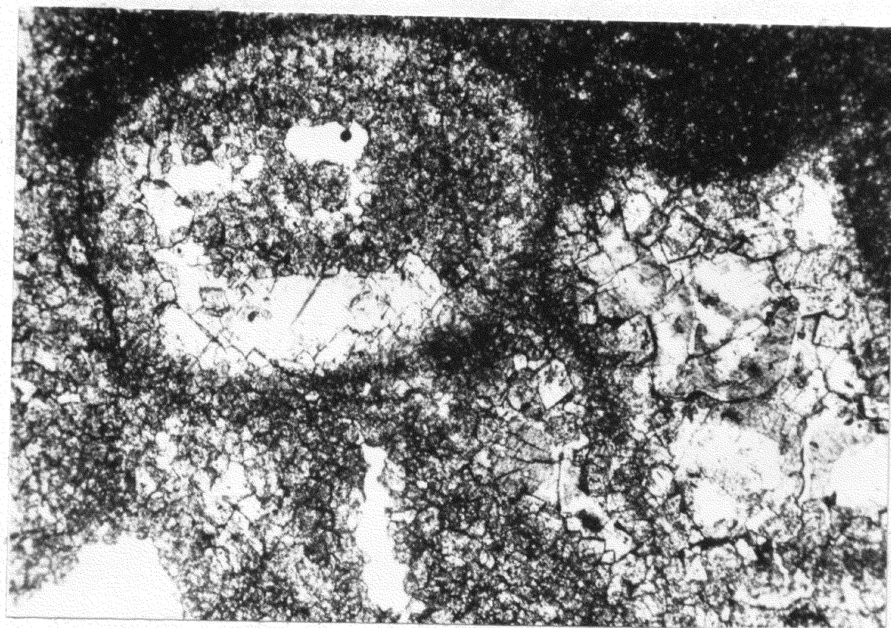


Fig. 1

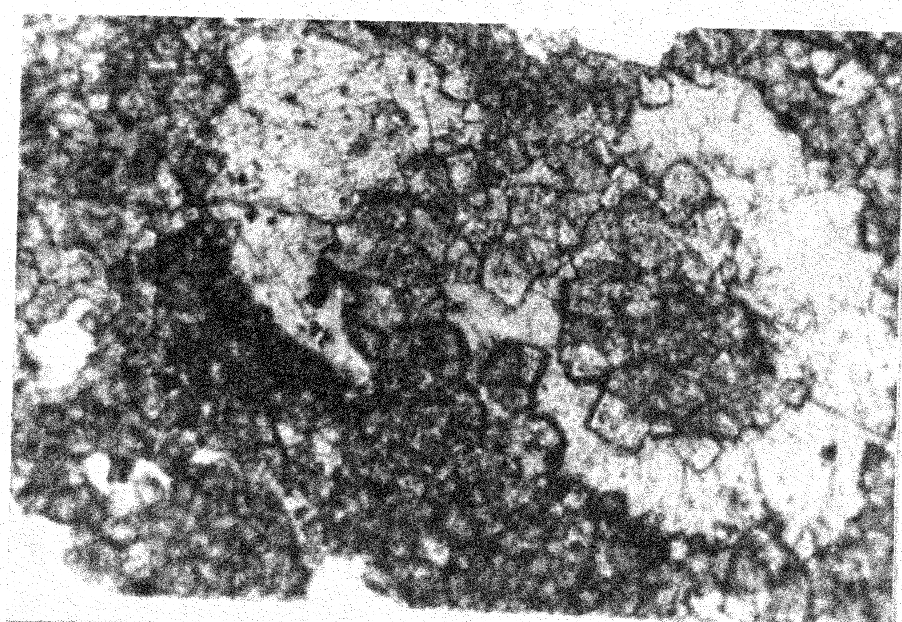


Fig. 2

PLATE 8

PLATE 9. PHOTOMICROGRAPHS

Figs. 1 and 2. These two photomicrographs show completely dolomitized crinoid columnals set in a cement of irregularly crystallized calcite and dolomite which is sometimes zoned (Z). Dolomitization has partially destroyed the structure of the fossil. x58.

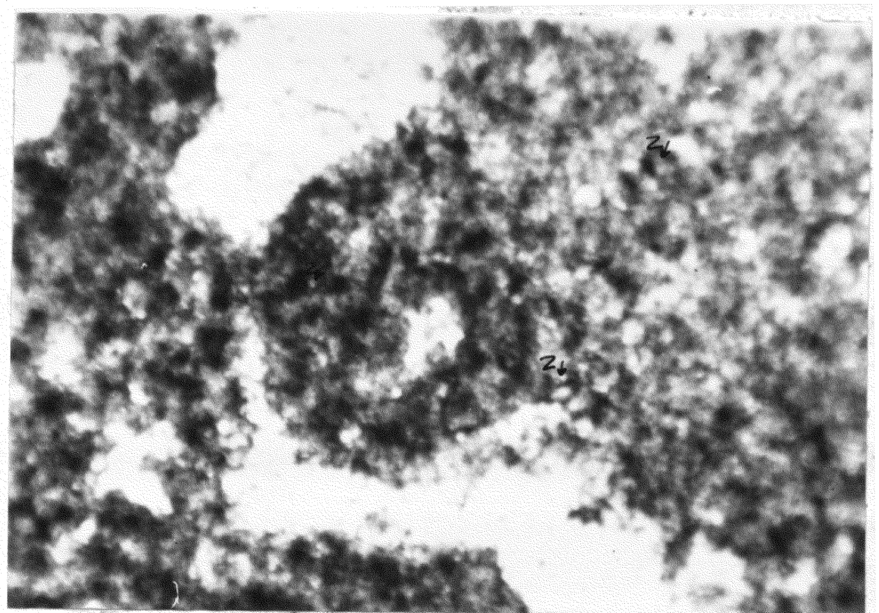


Fig. 1

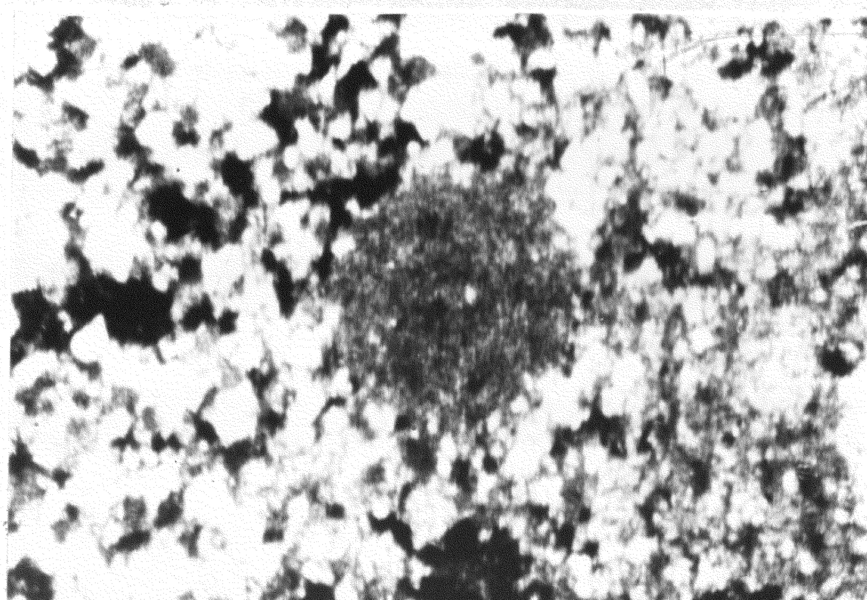


Fig. 2

PLATE 9

in the Pahasapa, also for the formation of coarse sparry calcite. If inter-fossil voids are filled by sparry calcite which forms continuous overgrowths on monocrystalline carbonate fragments, such as crinoid ossicles, spar will result. Here should be pointed out that diagenesis does not always operate to form larger crystals, and thus create sparry limestones.

Disregarding for a moment the process of recrystallization, the studies of modern carbonate deposits indicate that the filling of open spaces by precipitation of calcium carbonate may take place close to sea level. The open space precipitate mosaics of the Pahasapa Limestones likewise may have been formed close to sea level. Newell (1955, p. 303) discusses the condition under which calcium carbonate is precipitated in cavities at Laroia Atoll. Newell stated that the source of the calcium carbonate, precipitated so early in the primary pores of reef limestones, is derived from near-surface sea water, which tend to be supersaturated with calcium carbonate because they are warmed in the daytime over shallow reef flats, and because of photosynthesis by reef plants. During ebb tides, reef-flat waters are elevated a few inches above the surrounding sea, creating a weak hydrostatic head, which encourages the water to escape seaward by sinking through myriads of pores within the reef flat. Calcium carbonate is probably precipitated in transit.

3. Matrix alteration - The matrix of the Pahasapa shows

varying degrees of alteration; recrystallization is observed to have occurred in microcrystalline calcite producing pseudosparite. Another type of recrystallization, the syntaxial rim type is found mainly in the crinoidal biodolosparite, when a crinoid fragment is wholly or partly surrounded by dolomite which is a product of grain enlargement and dolomitization.

4. Altering of Allochems - Fossils are the most abundant allochem in the Pahasapa. Pellets and intraclasts are also present but in minor amounts of less than 10 percent.

   In sections studied in detail, fossils make up more than 90 percent of the allochems. Fossils in the Pahasapa are composed of dolomite except in a very few cases where they are composed of recrystallized calcite. Disregarding here the mechanism of dolomitization, the most important alteration of the fossils are discussed below:

   Crinoids: Initially crinoid columnals and plates consisted of a single crystal. After recrystallization, they are composed of many crystals. Crinoid stem segment originally have fine perforate structure, but calcite has filled the perforations and is oriented in optical continuity so that the perforations have disappeared in most plates (Plate 8, Fig. 1 and Plate 9, Figures 1 and 2). The hole in the columnal, the lumen, is filled with dolomicrite.

Brachiopods: Most of the shells of brachiopods are completely dolomitized and recrystallized. The inner layer of the brachiopod shells in the Pahasapa contain long slender dolomite prisms oriented obliquely to the shell surface. The internal cavity of the shell is filled with a fine to medium grained dolomite (Plate 2, Fig. 1).

Gastropods: Gastropods are not abundant in thin sections. Where gastropods shell do occur in the Pahasapa they have generally been completely altered to dolomitized sparry calcite.

Corals: The tabulate coral *Syringopora* is the only coral found in the Pahasapa at the study areas. It is interesting to note that the internal cavities of the corals are filled with calcite rather than dolomite spar.

Other Fossils: There are other fossils present in the Pahasapa Limestone. They consist of fragments of bryozoans, ostracodes, pelecypods, and others. The internal cavities of these fossils are filled with dark dolospar which also forms overgrowths on those components. This indicates either recrystallization on original carbonate mud or just simply cavity filling. The bryozoa zooecia are mainly filled with dolospar but also some dolomicrite, which also indicate recrystallization of a carbonate mud.

Ultimately the fossils are so altered that their identification becomes impossible.

Pellets: Pellets occur in the Pahasapa only sparingly as previously indicated. In all cases these pellets have been dolomitized making their structure very difficult to recognize. They consist of microcrystalline dolomite and are more or less uniform in size. In most cases their outer boundaries are hazy and grade into the surrounding matrix (Plate 10, Figures 1 and 2).

5. Dolomitization - The mineral dolomite occurs in the Pahasapa either as extensive dolomite mosaics (dolospar) with an equigranular texture or, less commonly, as isolated patches in either calcitic micrite or spar groundmass. The reason for believing the dolomites to be secondary in origin are the following: the occurrence of single dolomite rhombs in a limestone matrix and partial or complete obliteration of the primary texture. The depositional textures are often preserved as relict structures even though the rock has been replaced by crystalline dolomite.

Dolomitization, as Baars (1963, p. 127) stated, is the most difficult form of diagenesis to deal with, for it is the least understood of the diagenetic processes. Dolomitization occurs in varying degrees of severity in the limestones, but usually there is clear-cut evidence

PLATE 10. PHOTOMICROGRAPHS

Fig. 1. Poorly defined pellets (P) of dark impure dolomite are set in a groundmass of medium crystalline, light colored euhedral dolomite which contains some zoned dolomite crystals. A few scattered detrital quartz (Q) and pyrite (X) crystals are present. x58.

Fig. 2. Structureless pellets (P) in a perhaps recrystallized spar matrix. Many of these pellets range in size from 80 to 200 microns. The generally cloudy boundaries of the pellets indicate incipient recrystallization spreading from the cement into the pellets. x58.

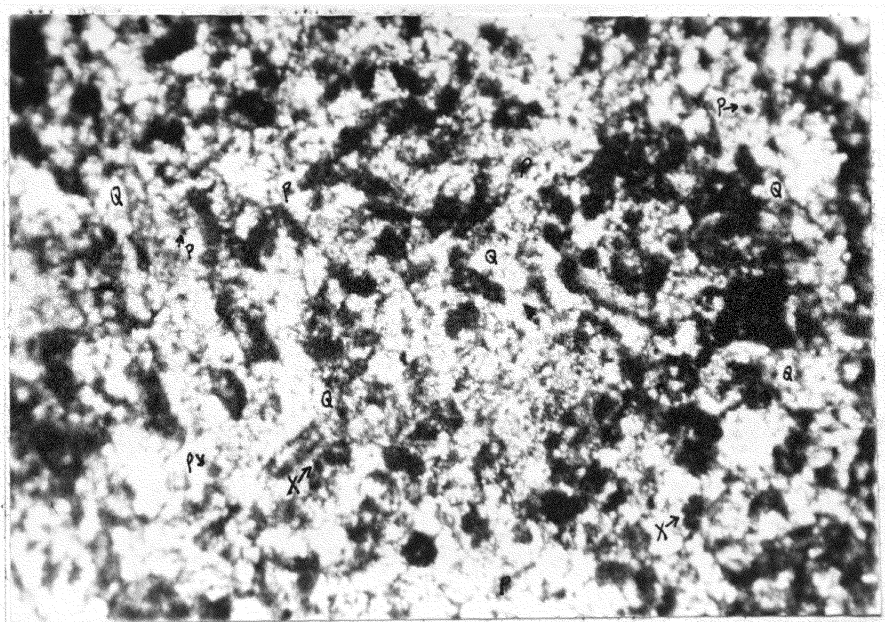


Fig. 1

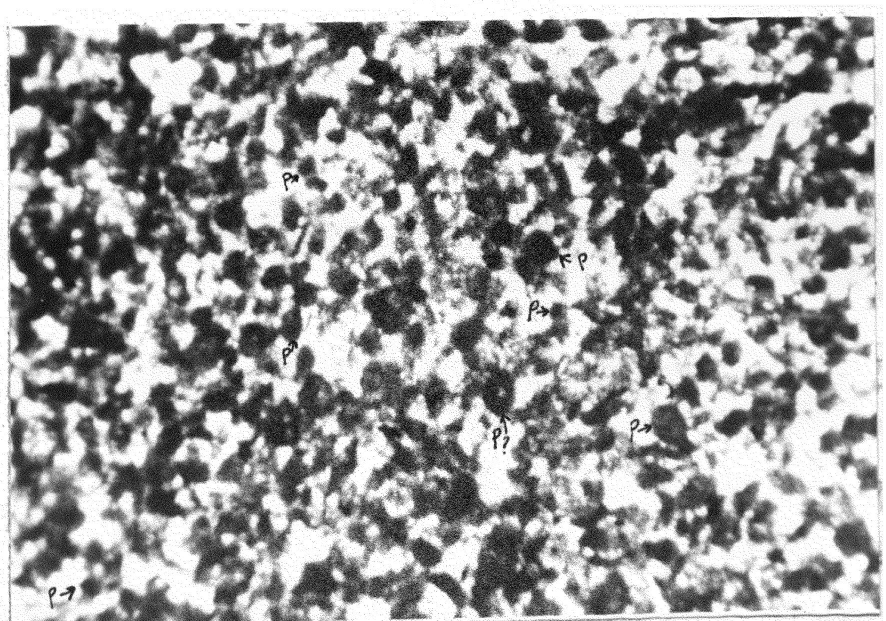


Fig. 2

PLATE 10

for alteration of pre-existing limestone instead of primary sedimentation.

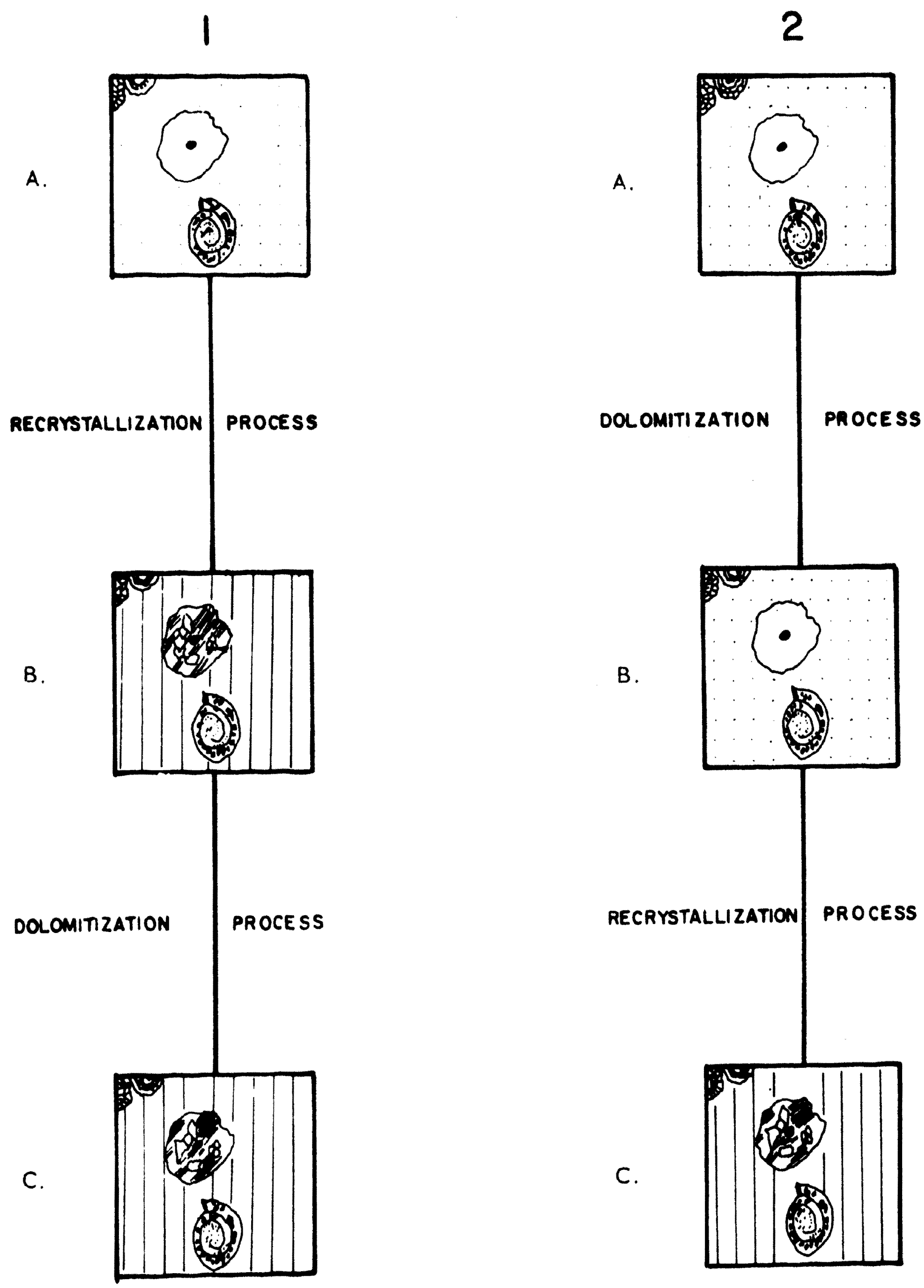
In Pahasapa the dolomitization has been mostly uniform. However, many cases are observed in thin sections where the dolomitization is patchy, selective and restricted to the finer grained textures. In partially dolomitized rocks of the Pahasapa certain carbonate constituents, particularily microcrystalline calcite are more readily replaced by dolomite than are other constituents. Microcrystalline calcite, whether as a matrix or as an infilling in the cavities of fossil debris, was selectively dolomitized in contrast to coarser grained allochems.

The writer believes dolomitization in the Pahasapa may have proceeded by one of the following steps (Fig. 18):

1. The original rocks were predominantly crystalline calcitic (micrite). These rocks were recrystallized to microspar and/or pseudospar and then were dolomitized to dolospar.
2. Again, the original rocks were microcrystalline calcite. By dolomitization, these rocks converted to dolomicrite. Later these dolomicrites were recrystallized to dolospar.

In both cases the dolomitization process ends with dolosparite. Unfortunately in the thin sections examined there is no strong evidence to support either one of these cases. Rock type 6, sparite, may be a case in which calcite spar had not yet been converted to dolosparite. No

Fig. 18. Alternative hypotheses by which the Pahasapa could have been dolomitized.



Two possible hypotheses by which the Pahasapa was dolomitized.

1. Rock dolomitized after matrix has been recrystallized to microspar and pseudospar. Only composition (not texture) changes in process of dolomitization.
   A. Original rock consists of micrite with some allochems (fossil).
   B. The original rocks recrystallize to spar, microspar, and pseudospar.
   C. Dolomitization of both spar and fossils to dolospar and pseudodolospar.
2. Matrix (micrite) dolomitized directly to dolospar, both grain size and composition changes.
   A. Original rock is micrite with calcitic fossils. Fossils usually crinoids, corals, or brachiopods.
   B. The matrix has dolomitized to dolomicrite.
   C. Recrystallization takes place after dolomitization. Both the matrix and fossils are dolomitized.

Fig. 18

example of transition of calcite to dolomite spar could be found in slides prepared of this rock type to support this idea.

McKinley (1951, pp. 169-183), discussed the theories relating to marine replacement of limestones to form dolomites. He postulates the following possibilities:

A. Penecontemporaneous replacement - McKinley believes that the replacement takes place immediately after deposition of the sediment, before consolidation into rock, and prior to superposition of any great thickness of additional material.

B. Syndiagenetic replacement - According to the same author, syndiagenetic dolomitization takes place during diagenesis of calcareous material, and should even be considered a factor in transformation of the sediment into rock.

C. Post-diagenetic replacement - McKinley indicated that this type of replacement occurs in the marine realm. He pointed out that this replacement involves alteration of the completely lithified limestone to dolomite by the action of sea water, or of static connate waters.

The writer believes the hypothesis A of McKinley is the most likely applicable explanation for the dolomitization of the Pahasapa Limestone. This will be explained in more detail in the next section.

C - Depositional Setting

One principal question posed in interpreting the depositional history of the Pahasapa is why are the Pahasapa Limestones dolomitized in the Black Hills especially in the study areas, whereas the Pahasapa is mostly limestones in the Williston basin and the adjoining areas? Inferences concerning depositional history of the Pahasapa are summarized below.

As noted from the gross Mississippian carbonate thickness isopach map (Fig. 19) prepared by Gries and Mickelson (1969, p. 110), the Mississippian carbonate rocks are variable in thickness. They are thicker toward the north and northeast of the Black Hills, South Dakota, and relatively thin in the Black Hills area. White and Merchant (1971, p. 12) report that the percentage of the dolomites in the Madison Group in Williston Basin, Wyoming, of which the equivalent Pahasapa forms a major part, averages about 14 percent. Compared to values determined in this study, we can see that the percentage of dolomite in the Black Hills is much higher than it is to north and east of the Black Hills.

In addition to being dolomitized, the fossil particles are generally fragmented, abraded and disarticulated. With these general observations in mind, as well as observations of microscopic characteristics, it is feasible to draw the following general conclusions concerning origin and depositional environment of the Pahasapa dolomites:

The Pahasapa Limestone in the study areas is interpreted to have been deposited as an irregular marine bank, which rose above

Fig. 19. Isopach map of the Mississippian rocks in South Dakota and adjacent areas. In the Black Hills area, this consists of the Englewood and Pahasapa Limestone. (After J. Gries and J. Mickelson, 1964).

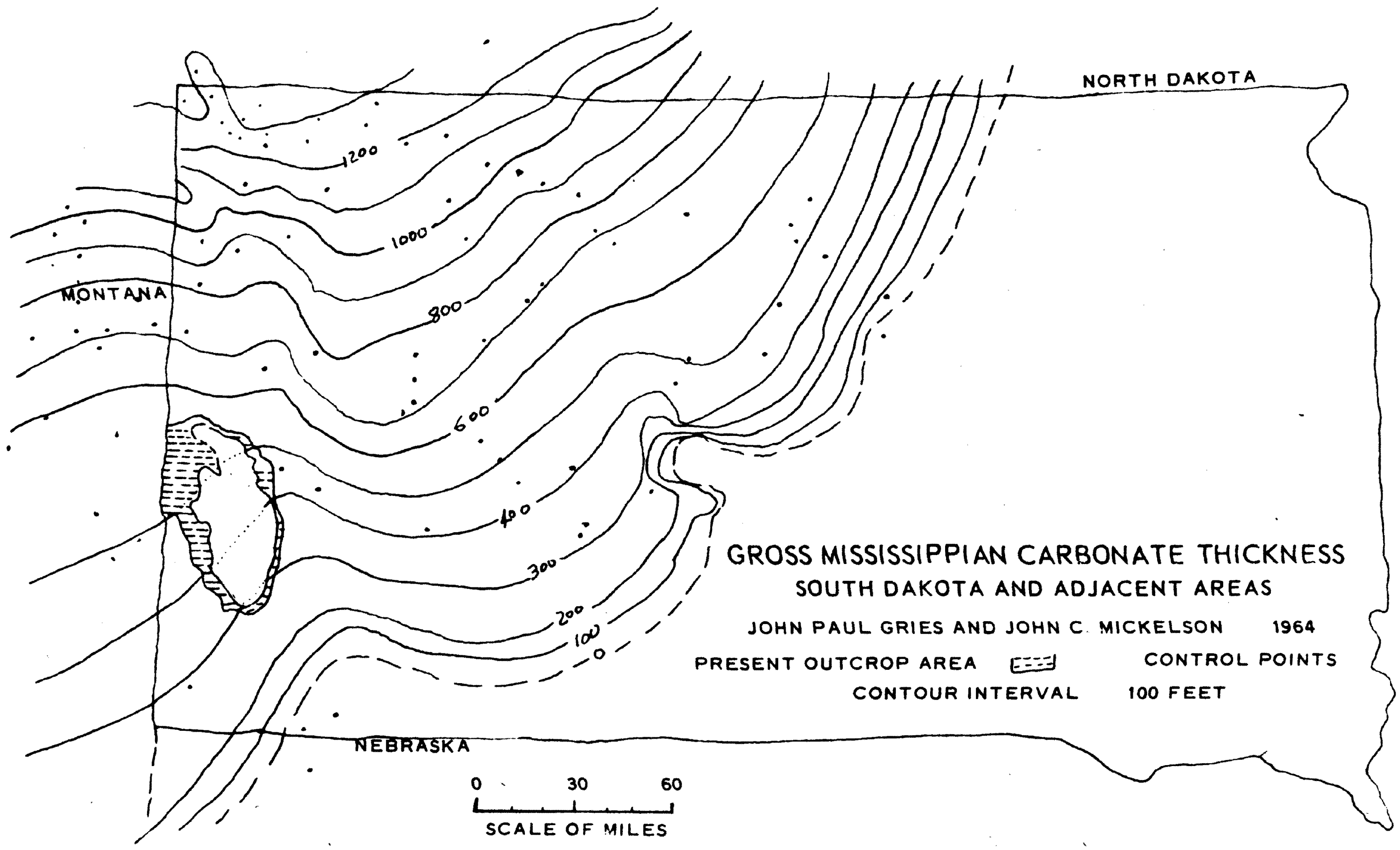

NORTH DAKOTA
MONTANA
NEBRASKA
1200
1000
800
600
400
300
200
100
0
GROSS MISSISSIPPIAN CARBONATE THICKNESS
SOUTH DAKOTA AND ADJACENT AREAS
JOHN PAUL GRIES AND JOHN C. MICKELSON 1964
PRESENT OUTCROP AREA
CONTROL POINTS
CONTOUR INTERVAL 100 FEET
0 30 60
SCALE OF MILES

Fig. 19

the general level of the surrounding sea floor. Evidence of this conclusion includes the presence of variable cross-beds, which imply depositional slopes and therefore relief on the sea floor as well as shallower water. (In most sections the cross-beds are dipping in different directions, e.g., at the Iron Creek Canyon locality is dipping northwest, and at the Little Elk Creek Canyon locality dips northeast.) Harbaugh (1959) has studied the Plattsburg Limestone in the Neodesha-Fredonia area of Kansas, pointing out that the presence of large cross-beds implies the existence of differences in elevation during deposition. He also stated that the variable dip directions of the cross-beds suggest that they were greatly affected by topographic irregularities, such as lobed projections of the bank. The Pahasapa Limestone likewise may have been formed on marine banks similar to that of the Plattsburg limestones. The relief and areal extent of these marine banks are not clear to the writer.

The lack of frame-building organisms suggests that the Pahasapa should not be considered to be a reef deposit, although the Pahasapa has certain reeflike aspects. The dolomitization process began at this marine bank where it is relatively high and shallow, and hence the waters on it had high salinity. This situation helps further diffusion, and permitted dolomitization solutions to spread. Table 2 summarizes depositional environments of the Pahasapa rock types in this study.

Two principal fabric types have been recognized in the Pahasapa Limestone. One is the predominant dolosparite fabric which is that formed through dolomitization and recrystallization of carbonate silt or fine skeletal debris by grain growth. The other fabric is that which has been formed through dolomitization of calcite mosaics that have been precipitated in open space.

This explanation of the dolomitization in the study areas may not be true. Many problems concerning the details of dolomitization in the study areas remain unsolved. More information is needed about the adjacent areas before any constructive suggestions can be made.

Now, that the dolomitization of Pahasapa has been interpreted previously in this section it is appropriate to consider the gross lithological features that bear on the depositional environment of the dolomite in the study areas. More specifically, the study of the many lithologies in the thesis area show they can all be classified into three main types:

1. Non-fossiliferous dolomites - The non-fossiliferous dolomites include rock types 1, 5, and 6 as listed on pages 41 and 44. These rock types are composed of compact, well-bedded, mottled dolomites in which the mottling is composed of microcrystalline dolomites. These rock types represent about 60 percent of the total composition of the Pahasapa.

   In the Iron Creek section, very poorly developed ghost pellets are observed floating in a dolospar matrix. These pellets are not easily recognized since they are small in size, composed of dolomite as is the matrix and possess no internal structure.

   The non-fossiliferous dolomite rocks may have been deposited in a shallow marine environment, which was poorly oxygenated; the evidence of that is the sparse fossil content in this rock type. High salinity, created in these shallow waters, may also have been a factor.

2. Fossiliferous dolomites - The fossiliferous dolomites represent 40 percent of the total. It is composed of rock types 2, 3, and 4. These rock types are nearly completely dolomitized. Some of the fossil fragments in these rock have been dissolved out and the molds filled by a drusy dolomite mosaic. The most common fossils found are: crinoid, brachiopods, corals, gastropods, and bryozoans.

   The abundant and varied fauna suggest well-oxygenated, quiet, shallow, sheltered water of normal salinity. Dolomitization may have destroyed the smaller and more delicate fossils, and only the larger fragments, such as large crinoid columnals have been preserved as ghosts of sparry dolomite.

3. Biodolointrasparite and Intrasparite - The grains in the intrasparite are sand- to pebble-sized intraclasts of rock types 1 and 5 (dolospar and biodolomicrite). In the biodolointrasparite, abundant fossil fragments are found together with the intraclasts and dolointraclasts. The cement between the grains is in part a drusy dolomite mosaic. The constituents of this rock type are mostly dolomitized.

   This latter rock type has been strongly affected by diagenetic alteration. Although it is easy to recognize the grains which make up this rock type, it is difficult to make out the original matrix or cement. The intraclasts of this rock type represent a penecontemporaneous erosion of lithified or semi-lithified carbonate sediment. In summary, deposition of these intrasparite rock types may have occurred in the following sequence. Firstly, deposition of lime mud in shallow water as described above, followed by erosion of this semi-consolidated lime mud. Secondly, the resulting intraclasts were transported to an even more shallow water environment. Such an environment could be shelf lagoon (?) in a situation where waves break over shoals along the edge of the carbonate bank.

SUMMARY AND CONCLUSIONS

1. The Mississippian Pahasapa formation was studied in the north-eastern quadrant of the Black Hills, South Dakota; the carbonate which makes up all of this formation is primarily a dolomite in this area. Seven sections were studied; one of these seven sections was a complete section and the other six were partial.
2. On the basis of petrographic studies, the dolomites of the Pahasapa can be grouped into four general types:

   A. Fossiliferous dolomite

   B. Non-fossiliferous dolomite

   C. Sparite

   D. Intradolomite

   More specifically, they can be classified into eight types using the carbonate terminology of Folk (1959 and 1962) and that of Schmidt (1965):

   1. Dolosparite
   2. Biodolosparite
   3. Crinoidal biodolosparite
   4. Biodolomicrite
   5. Dolomicrite
   6. Sparite
   7. Intrasparite
   8. Dolointramicrite
3. The distribution of these dolomite constituents is shown by bar diagrams for the various beds in the stratigraphic sections (Figs. 11-17). Because of the sparse sampling and the simplified

data, no boundaries between rock types are drawn in the column. The rock type boundaries are, in fact, usually gradational.

4. The occurrence of dolomite is not confined to distinct beds or groups of beds.

5. Some of the Pahasapa carbonates contain an abundant fauna of brachiopods, corals, and crinoids indicative of deposition in shallow water under moderate to high energy conditions. It seems likely that many of these organisms lived at depths of considerably less than 200 feet. The proportions of crinoids and brachiopods tend to vary similarly suggesting that these organisms responded similarly to changes in environmental conditions.

6. Two principal fabric types have been recognized in the Pahasapa Limestone. One is the fabric of calcite mosaic that have been precipitated in open space. The other fabric is that of calcite and dolomite mosaics formed through recrystallization of fine grained carbonate materials.

7. Pores tend to be localized (a) along fractures, (b) within coarsely crystalline open-space precipitate mosaics, (c) at the contact of crystalline mosaics and, (d) within dolomitized patches.

8. The Pahasapa Limestone is interpreted to have been deposited as a broad marine bank. High salinity was an important factor in the dolomitization of this rock which is considered to be penecontemporaneous in origin.

9. Reefs were not established in the area studied possibly because of lack of frame-building organisms although the Pahasapa has

certain reeflike aspects.

BIBLIOGRAPHY

Agatston, R. S., 1954, Pennsylvanian and Lower Permian of northern and eastern Wyoming: Amer. Assoc. Petrol. Geol. Bull., vol. 38, pp. 508-583.

Andrichuk, J. M., 1955, Mississippian Madison Group stratigraphy and sedimentation in Wyoming and southern Montana: Amer. Assoc. Petrol. Geol. Bull., vol. 39, no. 11, pp. 2170-2210.

Baars, D. L., 1963, Petrology of carbonate rocks, in Bass, R. O., ed., Shelf carbonates of Paradox basin - A Symposium: Four Corners Geol. Soc., 4th Field Conf., pp. 101-129.

Bathurst, R. G. C., 1958, Diagenetic fabrics in Some British Dinantian Limestones: Liverpool and Manchester Geol. Jour., vol. 2, pp. 11-36.

Beales, F. W., 1958, Ancient sediments of bahamian type: Amer. Assoc. Petrol. Geol. Bull., vol. 42, pp. 1845-1880.

__________, 1965, Diagenesis in pelleted limestones, in Pray, L. C., and Murray, R. C., eds., Dolomitization and limestone diagenesis - a symposium: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 13, pp. 49-70.

Bogglid, O. B., 1930, The shell structure of the mollusks: D. Kgl. Danske Vidensk. Selsk., Skrifter, Naturvidensk, Ogmathem. Afd., Ser. 9, vol. 2, no. 2, pp. 233-326.

Blackstone, D. L., Jr., and McGrew, P. O., 1954, New occurrence of Devonian rocks in north central Wyoming: Billings Geol. Soc. Guidebook, 5th Ann. Field Conf., pp. 38-43.

Brobst, D. A. and Epstein, J. B., 1963, Geology of the Fanny Peak Quadrangle, Wyoming-South Dakota: U. S. Geol. Survey Bull. 1063-I, pp. 325-327.

Carozzi, A. V., 1960, Microscopic sedimentary petrography: New York, John Wiley and Sons, Inc., 485 pp.

Cayeux, Lucien, 1931, Introduction à l'etude petrographique des roches sedimentaires: Paris, Imprimerie Nationale, 2 vol., 524 pp.

Chilingar, G. V., Bissell, H. J., and Fairbridge, R. W., eds., 1967, Carbonate rocks: New York, Elsevier Publishing Co., parts 9A and 9B.

Darton, N. H., 1901, Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining areas in South Dakota and Wyoming: U. S. Geol. Survey, 21st Ann. Report. Pt. IV, pp. 508-509.

__________, 1905, Description of the Sundance Quadrangle, Wyoming and South Dakota: U. S. Geol. Survey Geol. Atlas, Folio 127, 12 pp.

__________, 1909, Geology and water resources of the northern portion of the Black Hills and adjoining regions in South Dakota and Wyoming: U. S. Geol. Survey Prof. Paper 65, 20 pp.

__________, and Paige, Sidney, 1925, Description of the central Black Hills: U. S. G. S. Geol. Atlas Folio 219, 7 pp.

Dobbin, C. E., and Reeside, J. B., Jr., 1929, The contact of the Fox Hills and Lance Formations: U. S. Geol. Survey Prof. Paper 158-B, p. 9-25.

Eardley, A. J., 1949, "Paleotectonic and paleogeologic maps of central and western North America": Amer. Assoc. Petrol. Geol. Bull., vol. 33, no. 5, pp. 655-683.

__________, 1959, Practical Petrographic classification of limestones: Am. Assoc. Petrol. Geol. Bull., vol. 43, pp. 1-38.

__________, 1962, Spectral subdivision of limestone types, <u>in</u> W. E. Ham, ed., classification of carbonate rocks - a symposium: Am. Assoc. Petrol. Geol. Mem. 1, pp. 62-84.

Folk, R. L. and Weaver, C. E., 1952, A study of the texture and composition of chert: Amer. Jour. Sci., vol. 250, pp. 498-510.

__________, 1965, Some aspects of recrystallization in ancient limestones, <u>in</u> Pray, L. C., and Murray, R. C., eds., Dolomitization and limestone diagenesis - a symposium: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 13, pp. 14-48.

Foster, N. H., 1960, Faunal zonation and stratigraphy of the Mississippian Madison group, northeastern Big Horn Mountains, Wyoming: Unpub. M. S. Thesis, state Univ. Iowa.

Friedman, G. N., 1959, Identification of carbonate minerals by staining methods: Jour. Sed. Petrol., vol. 29, pp. 87-97.

__________, 1964, Early diagenesis and lithification in carbonate sediments: Jour. Sed. Petrology, vol. 34, pp. 777-813.

__________, and Sanders, J. E., 1967, Origin and occurrence of dolomite, <u>in</u> Chilingar, G. V., Bissell, H. J., and Fairbridge, R. W., eds., carbonate rocks, pt. A: New York, Elsevier Publishing Co., pp. 267-348.

Ginsburg, R. N., 1956, Environmental relationships of grain size and constituent particles in some south Florida carbonate sediments:

Am. Assoc. Petroleum Geolog. Bull., vol. 40, pp. 2384-2427.

__________, 1957, Early diagenesis and lithification of shallow-water carbonate sediments in south Florida, in Regional aspects of carbonate deposition: Soc. Econ. Paleontologists and Mineralogists, Special Pub. 5, pp. 80-99.

__________, and Lowenstam, H. A., 1958, The influence of marine bottom communities on the depositional environments of sediments, Jour. Geology, vol. 66, pp. 310-318.

Gries, J. P., and Mickelson, J. C., 1964, Mississippian carbonate rocks of western South Dakota and adjoining areas: 3rd Internat. Williston Basin Symposium, Regina, Saskatchewan, pp. 109-118.

Harbaugh, J. W., 1959, Marine bank development in Plattsburg Limestone (Pennsylvanian), Neodesha-Fredonia area, Kansas: Kansas Geol. Survey, Bull. 134, Pt. 8, pp. 289-331.

__________, 1960, Petrology of marine bank limestones of Lansing group (Pennsylvanian), southeast Kansas: Kansas Geol. Survey Bull. 142, pp. 189-234.

__________, 1961, Relative ages of visibly crystalline calcite in late Paleozoic limestones: Kansas Geol. Survey Bull. 152, pp. 91-126.

Illing, L. V., 1954, Bahamian calcareous sands: Am. Assoc. Petroleum Geol. Bull., vol. 38, pp. 1-95.

__________, Wells, A. J., and Taylor, J. C. M., 1965, Penecontemporary dolomite in the Persian Gulf, in Pray, L. C., and Murray, R. C., eds., Dolomitization and limestone diagenesis - a symposium: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 13, pp. 89-111.

Jaggar, T. A., Jr., 1901, The laccoliths of the Black Hills: U. S. Geological Survey 21st Ann. Report, Pt. III, pp. 180-181.

Johnson, J. H., 1951, An introduction to the study of organic limestones: Colorado School of Mines Quart., vol. 46, no. 2, 185 pp.

__________, 1957, Petrography of the limestones in Geology of Spain, Mariana Islands: U. S. Geol. Survey, Prof. Paper 280-C, pp. 177-187.

Katz, Amitai, and Friedman, G. M., 1965, The preparation of stained acetate peels for the study of carbonate rocks: Jour. Sed. Petrology, vol. 35, pp. 248-249.

Klapper, Gilbert, and Furnish, W. M., 1962, Devonian-Mississippian Englewood formation in Black Hills, South Dakota: Amer. Assoc.

Petrol. Geol. Bull., vol. 46, no. 11, pp. 2071-2078.

Kume, J., 1963, The Bakken and Englewood formations of North Dakota and northwestern South Dakota: North Dakota Geol. Survey, Bull. 39, pp. 14-28.

Laborte, L. F., 1967, Carbonate deposition near mean sea level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York state: Am. Assoc. Petroleum Geologists Bull., vol. 51, pp. 73-101.

Leighton, M. W., and Pendexter, C., 1962, Carbonate rock types, in classification of carbonate rocks: Am. Assoc. Petroleum Geologists Mem. 1, pp. 33-61.

Love, J. D., Weitz, J. L., and Hose, R. K., 1955, Geologic map of Wyoming (1:500,000): U. S. Geol. Survey.

Lowenstam, H. A., and Epstein, S., 1957, On the origin of sedimentary aragonite needles of the Great Bahama Bank: Jour. Geol., vol. 65, pp. 364-375.

McKinley, M. E., 1951, The replacement origin of dolomite - a review. The Compass, Sigma Gamma Epsilon, vol. 28, pp. 169-183.

Mandelbaum, H., and Sanford, T. J., 1952, Table for computing thickness of strata measured in a traverse or encountered in a bore hole: Bull. Geol. Soc. America, vol. 63, pp. 765-776.

Moore, H. B., 1939, Faecal pellets in relation to marine deposits, in Trask, P. D., ed., Recent marine sediments - a symposium: Am. Assoc. Petroleum Geologists Bull., pp. 516-524.

Murray, R. C., 1960, Origin of porosity in carbonate rocks: Jour. Sed. Petrology, vol. 30, pp. 59-84.

Newell, N. D., 1955, Depositional fabric in Permian reef limestones: Jour. Geol., vol. 63, pp. 301-309.

__________, and Rigby, J. K., 1957, Geological studies on the Great Bahama Bank, in Le Blanc, R. J., and Breeding, J. G., eds., Regional aspects of carbonate deposition - a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 5, pp. 15-72.

__________, Purdy, E. G., and Imbrie, John, 1960, Bahamian oolitic sand: Jour. Geology, vol. 68, pp. 481-497.

Orme, G. R., and Brown, W. W. M., 1963, Diagenetic fabrics in the Avonian limestones of Derbyshire and North Wales: Yorkshire Geol. Soc. Proc., vol. 34, Pt. 1, no. 3, pp. 51-66.

Purdy, E. G., 1963, Recent calcium carbonate facies of the Great

Bahama Bank: 1. Petrography and reaction groups: Jour. Geology, vol. 71, pp. 334-355.

Robinson, C. S., Mapel, W. J., and Bergendahl, M. H., 1964, Stratigraphy and structure of the northern and western flanks of the Black Hills uplift, Wyoming, Montana, and South Dakota: U. S. Geol. Survey, Prof. Paper 404.

Ruedemann, R., and Lockman, C. Balk, 1942, Graptolites from Englewood Formation (Mississippian) of the Black Hills, South Dakota: Jour. of Paleontology, vol. 16, pp. 657-659.

Sbeta, A., 1970, Geology and petrography of Hosselkus Limestone, Shasta county, California: unpublished M. S. Thesis, Stanford University.

Schmidt, V., 1965, Facies, diagenesis, and related reservoir properties in the Gigas beds (Upper Jurassic), northwestern Germany, in Pray, L. C., and Murray, R. C., eds., Dolomitization and limestone diagenesis - a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 13, pp. 124-168.

Shinn, E., 1964, Recent dolomite, Sugarloaf Key, in South Florida carbonate sediments: Geol. Soc. America Field Guidebook no. 1 (compiled by R. N. Ginsburg).

__________, Ginsburg, R. N., and Lloyd, M. R., 1965, Recent supratidal dolomite from Andros Island, Bahamas, in Pray, L. C., and Murray, R. C., eds., Dolomitization and limestone diagenesis - a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 13, pp. 112-123.

Siegel, F. R., 1961, Factors influencing the precipitation of dolomitic carbonates: State Geological Survey of Kansas, Bull. 152, pp. 129-158.

Sorby, H. C., 1879, Structure and origin of limestones: Geol. Soc. London Proc., vol. 25, pp. 56-95.

Stauffer, K. W., 1962, Quantitative petrographic study of Paleozoic carbonate rocks, Caballo Mountains, New Mexico: Jour. Sed. Petrology, vol. 32, pp. 357-397.

Swenson, F. A., 1968, New theory of recharge to the Artesian Basin of the Dakotas: Geol. Soc. of America Bull., vol. 79, pp. 163-182.

Teodorovich, G. I., 1958, Study of sedimentary rocks. Gastoptekhizdat, Leningrad, 572 pp.

Terry, R. D., and Chilingar, G. V., 1955, Comparison chart for estimating percentage composition: Jour. Sed. Petrology, vol. 25, no. 3, pp. 229-234.

Van Siclen, D. C., 1958, Depositional topography - examples and theory: Am. Assoc. Petroleum Geol. Bull., vol. 42, pp. 1329-1413.

Vishnyakov, S. G., 1951, Genetic types of dolomite rock. Dokl. Akad., Nauk, U.S.S.R., vol. 76, no. 1, pp. 112-113.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Sed. Petrology, vol. 30, no. 2. pp. 283-296.

White, E. J., and Marchant, L. C., 1971, Evaluation of the Madison Limestone in Williston basin from well logs and cores. U. S. Bur. of Mines, Report of Investigations Publ. no. 7497, pp. 1-27.

Wolf, K. H., 1965, Petrogenesis and paleoenvironment of Devonian algal limestones of central New South Wales: Sedimentology, vol. 4, pp. 133-178.

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